Master Final Thesis

Energy Engineering – Renewable Energies

Feasibility study of energy projects to be applied to the water cooling system of a factory in Barcelona following the Working Class Manufacturing methodology

MEMÒRIA

Autor: Lorenzo Petrini
Director: Oriol Gomis Bellmunt
Convocatòria: Septiembre 2018

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

UPC

Abstract

The focus of this work is the application of 3 different technologies to the water cooling system that supply chilled water to the machines employed in an industrial plant in Barcelona, to cut the electricity consumption or to substitute it with the local renewable generation.

These technologies consist in a photovoltaic installation of 100 kW_{el}, that is the maximum power allowed by the law, an absorption chiller that exploit the waste heat of the air compressors in the plant to generate chilled water and a stratified chilled water tank, adapted from a water deposit already present next to the building for firefighters use, employed to store chilled water in the night time, generated with the already present chillers when the electricity cost is the lowest to utilize it when needed during all the day long.

The Working Class Manufacturing methodology has been followed as it is common when developing a project in the plant. To develop the project instead, all the knowledge absorbed during the engineering studies of the author as been employed. To design the photovoltaic field a software is utilized. The absorption chiller is modelled with basic thermodynamic principles and with correlations founded in the literature. The thermal storage is modelled with transient partial differential equations, solved with a MATLAB code.

The objective of the work, that consist in respecting an emission target, is reached. Moreover, the economic analysis shows a possible rentability.

Index

ETSEIB

1. Glossary

5W + 1H WHAT / WHERE / WHEN / WHICH / WHO / HOW to position the phenomenon within these items

AC Alternate current

B/C Benefit/Cost (It is an indicator needed to evaluate roughly, in the year, if an investment is convenient or not, simply watching if it is higher or lower than the unity)

BP Best Practique (It is a standardized project i.e. a valid project applied in one plant that could be repeated in all the plants of the group)

CD Cost Deployment

COP Coefficient of Performance

cos φ power factor

DC Direct current

EMF Electromagnetic field

Emf Electromotive force

ET Energy term

GHP Good Hours Produced (It is an indicator for saying how much of the production time is generating good pieces i.e. the ones accepted by the quality department)

HVAC Heating, Ventilation and Air Conditioning

KPI Key Performance Indicators - Objective results indicators

kW_{el} / kWh_{el} Electric Kilowatt / Kilowatt-hour

kW_{ng} / kWh_{ng} Kilowatt / Kilowatt-hour referred to the HV of the natural gas

kW_{th} / kWh_{th} Thermal Kilowatt / Kilowatt-hour

MPPT Maximum Power Point Tracking

P_{ph} active power of 1 phase

PSOL Software employed to simulate the photovoltaic field

PT Power term

SCRAP Defective pieces that are rejected by the quality department

SI International System of Units

Smc Standard Cubic Meter

TES Thermal Energy Storage

$\mathbf{V_{ph}}$ voltage of 1 phase

WCM Working Class Manufacturing

WIP work in process

1.1. Photovoltaic field

G radiation

PSOL Software utilized to simulate the system

MPPT maximum power point tracking

I current (**Isc** short circuit current, **Impp** maximum power point current)

V voltage (**Voc** open circuit voltage, **Vmpp** maximum power point voltage)

P power

FF fill factor

Tc cell temperature

1.2. Absorption chiller

G generator (**Qg, Tg**)

C condenser (**Qc**)

E evaporator (**Qe, Te**)

A absorber (**Qa**)

V valve

To ambient temperature

1.3. Stratified chilled water storage tank

T temperature [K]

c specific heat [J/kg/K]

ρ density [kg/m^3]

k thermal conductivity [W/m/K]

α thermal diffusivity [m^2/s]

v kinematic viscosity [m^2/s]

L_d diffusers total length [m]

hi diffuser height [m]

q maximum mass flow rate x unit length of diffusers [m^2/s]

D diameter [m]

L tank height [m]

R radius [m]

A surface of the fluid/wall section [m^2]

δ thickness (of the wall or of the insulation) [m]

P circle perimeter [m]

V tank volume [m^3]

m mass flow rate of the fluid in charging/discharging mode [kg/s]

w fluid velocity [m/s]

h convective heat transfer coefficient [W/m/K]

t time [s]

x space dimension [m]

Z mixing coefficient [-]

R_e Reynolds number [-]

R_i Richardson number [-]

FOM figure of merit [-]

C,S coefficient of the correlation

Subscripts

f fluid (water)

ins insulation

w wall

o outside (ambient)

∞ ambient

i inside (tank)

t top

b bottom

ch charging

disch discharging

h hot

c cold

1…N tank discretization

All the indices not reported are explained after their first introduction to lighten the glossary.

2. Introduction

2.1. Objective of the project

The project objective is the application of countermeasures to cut the electricity consumption or to substitute it with the local renewable generation. The motivations derive by its potential economical savings and by the good image that the plant will obtain thanks to the contribution in the fighting of the climate changes that is one of the major concerns nowadays. In fact, the local renewable generation and the energy efficiency projects impact in the cut of the use of conventional sources of energy by the country, so in the emission of carbon dioxide that is the main pollutant with world climatic changing effects.

Furthermore, the European policies after the Kyoto Protocol are imposing a limit in those emissions, which must be respected by the plant in order to not incur in legal problem. For example, external audits are performed to verify those conditions, like the ISO 50001 as well internal ones like the WCM audit which success will fix the objective of this project. The acronym WCM is for Working Class Manufacturing, that is the organization system of the company and the method followed for developing the project.

2.2. Scope of the project

To reach the scope of the project, that is the cutting of greenhouse gases emissions of carbon dioxide, a KPI, between the various ones monitored in the plant, will be verified in the conclusions. This indicator is the ratio between CO2 emissions and Good Hours Produced. From an environmental point of view the lower it is the better it is. The target fixed by the WCM audit for closing the year 2019 is 0,0126 tnCO2/h, but the results of 2017 were of 0,0127 tnCO2/h. The year 2019 is considered because it is assumed that the new technologies installed will be in function for the end of the 2018.

Given those numbers, the scope of the project is clearly defined, and it coincides with keeping the KPI of 2019 within the limits.

3. The industrial plant

3.1. Building structure

The Plant is located in Llinars del Vallès, Spain. It is a factory, of a multinational company, that combines man work and various technologies to produce headlights for motor vehicles. To obtain the final product the principal steps are: injection of molten plastic in specific molds, metallization of the plastic pieces and assembly of all the parts, electric parts comprised. It may be pointed that the electric parts are not manufactured in the place but bought from third party.

Considering these three main activities, the building is composed by the Injection area, two metallization areas and three assembly areas. Moreover, it is composed by the raw material and WIP warehouses, the laboratories, the various offices, the maintenance workshop, the canteen and some external parts. Parts of the same company is another building in the same district, called Pujol, that is also a warehouse but is the place where the logistic administration is carried out.

Title	Area	Surface [m^2]	Activity
A1	INJECTION 1	1.76	Injection of the plastic in the molds. The injected parts obtained are: bodies, transparent and auxiliary parts.
A2	CANTEEN	156	Lunch.
	LABORATORIES	395	Research and test activities.
A3	INJECTION 2	808	This area will be considered part of the A1 since there isn't any physical wall between them
A4	METALIZATION 1	1.026	Process by which the body and/or auxiliary parts are applied an aluminium layer in those areas that must be reflective.
A5/6/7	ASSEMBLY	5.427	Process through which all the components of the article (body, auxiliary parts and transparent) are assembled to obtain the final product called pilot.
A8	RAW MATERIAL WAREHOUSE	678	Storage of plastic pellets for injection molding.
	WIP WAREHOUSE	1.352	Storage of those parts that still need to be completed.
	PUJOL WAREHOUSE	3.132	Storage of the final product and components. Headquarter of logistic activities.
A9	METALIZATION 2	1.23	Same activities of metallization 1, but since they are divided they will be considered as two different areas
A10	MAINTENANCE WORKSHOP	587	Mold & general maintenance.
	OFFICIES	2.35	Administration.
	EXTERIORS	2.137	Storage of oils, common and hazardous residuals. Moreover, is the place where the battery bank and the 3 transformers are placed (this equipment will be examined further on).

Table 3.1 - Areas division, surface occupied, and activity performed

Figure 3.1 - Plan of the factory divided in operating areas. The arrows show the production regime flow.

3.2. Production regime

As explicated in the previous section the first step in the production of the final product is the manufacturing of the plastic part that therefore needs a supply of raw material in the form of polymer granules which quantity is reported in the below Tab.3.2 together with the total produced goods for the year 2017.

Plastic raw material [tn]	Annual headlamps produced	Daily headlamps produced
4.312	4.806.124	21.456

Table 3.2 - Production regime

To ensure this production regime the employees works uninterruptedly from Monday to Friday organizing shifts between the day-time, from 06:00 till 23:00 and the night-time, from 23:00 till 06:00. An approximation, that will be useful further on, is that the volume of production in the night-time is around the half of the day-time. This volume of production is in turn in the weekend the half of the other days.

Apart from these shifts it is relevant that the injection areas are operative in the weekends with production volumes near to the nominal ones, requiring a certain amount of chilled water as it will be clarified in the following chapters. This because most of the machines utilized in those areas don't need personal to produce.

3.3. Organization

The organization of the plant follows the World Class Manufacturing (WCM) methodology. It is a system developed in the USA in the 90', nowadays applied by different companies that operate in the industrial manufacturing sector [1].

Its philosophy is the creation of the perfect product to be sold in the market, so the one that has the highest possible quality at a competitive price. To make the price competitive, all the activities in the productive process must be reviewed and optimized, leading to the elimination of the waste, the increase of efficiencies and the enhancement of the quality. All this respecting the safety, the working conditions and the environment.

The administration structure is based on 10 pillars departments:

1. Safety - Workplace Safety control
2. Cost Deployment - Individuation of economic loss sources
3. Focus Improvement - Focused improvement of a specific problem
4. Workplace Organization - Care about the workplace conditions
5. Professional Maintenance - Machine technique maintenance
6. Quality Control - Respect of the customer's requests
7. Logistic - Information and parts flow administration
8. Early Equipment Management, Early Product Management - Strategy of acquisition of work / process media
9. <u>Environment & Energy</u> - Environment and exploitation of energy servomotors (For the sake of this study the characteristics of this pillar department are going to be discussed, focusing more on the Energy aspects)
10. People Development – Recruit and development of the staff

The activities performed by each pillar are linked to 7 steps and continuous internal audit (to not be confused with the external audit as the ISO 50001) are done to assure the correct evolution of the tasks. The steps for all the pillars are, in general:

1. Selection of model areas
2. Investigation
3. Measurement

4. Analysis
5. Countermeasures
6. Standardization
7. Horizontal expansion

Due to the nature of this project, the 7 steps of the 9th pillar that include the energy administration of the factory are going to be listed. In fact, for the development of every project under the WCM methodology, these steps must be followed. Nevertheless, this study is going to focus on the engineering aspect, so not all the activity done in the routine of the plant will be reported, giving more space to the technical considerations.

3.4. 7 Steps of the Energy Pillar

To facilitate the comprehension of the pursuit that the Energy department follows in its routine, each step is going to be explained, introducing the tools used and the activities undertaken.

3.4.1. Step 1: Selection of model areas

The main activities that are done in this first step are:

- Appoint a responsible person for the energy issues and form a team, providing adequate financial, technical and administrative supports
- Identify the energy issues (electric, gas, etc.) the plant must deal with
- Calculate economic impact by dealing with the identified energy issues. Make a Pareto for energy consumption (Electric, gas consumption, etc.)
- Audit the processes in the operation from an energy consumption perspective to prioritize energy issues according to potential savings
- Select the major energy consumption equipment and choose model areas to attack the identified energy issues (in the selection of these equipment apart the high energy consumption it should also considered if they have a high possibility of horizontal expansion of the know-how created to other line or equipment and if they consume much energy even at the time of reduced production)
- Set the objectives and targets (already exposed in the introduction)

As it is clear, this first step, apart from the creation of a specialized team, is thought to create an energy image of the factory, that is the first thing needed to identify the various week points in term of energy efficiency. These week points are identified as “model areas”, i.e. the areas that could be modelled to enhance the whole efficiency of the plant.

It is useful, for this step, to outline the energy consumption as it is done in the Fig.3.3. There are two carriers that correspond to the sources i.e. electricity and natural gas, they go through different transformations before to be exploited in the point of use after being transmitted in a certain form.

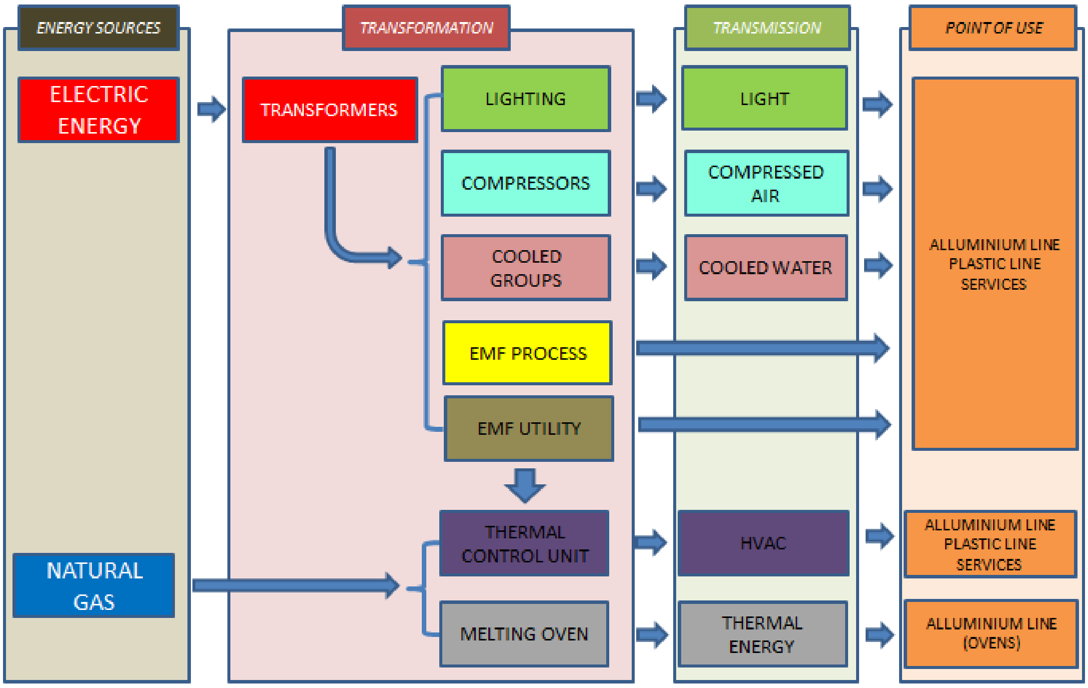


Figure 3.2 - Evolution of the energy carriers, from the sources to the point of use through different transformations. This example is the aluminum or plastic line services.

3.4.2. Step 2: Investigation

After the selection of the model areas, this next step is thought for investigating the line and the equipment that are comprised in that area. The investigation is done to the outline of the process, to the equipment system and its capacity, to the set condition and finally to the production situation and operation situation.

To define the usage and transformation map the 5W+1H tool is implicitly employed. It consists in the answer of six questions that for instance could be:

1. What is the equipment? Electrical motor, boiler, etc.
2. Where is located? Line, area
3. When is used? Always / during production
4. Who uses/manages it? Workers, supervisor, etc.

5. Why is used? Which operation, procedure
6. How much energy is consumed? A physical value, usually in kWh

This analysis should always include: the consumption driver i.e. which factors influences the consumption, the installed power and the function mode (always operating, operating when production etc.).

3.4.3. Step 3: Measurement

To have a clearer image of the energy profile in terms of number this step is needed. The main activities are:

- Choosing measuring points and effective measurement methods
- Understanding the fixed part and the variable part of energy consumption
- Understanding the situation of energy consumption over time
- Employees energy awareness (communications, brochures)
- Establish an audit system (with the use of calendars the supervisor, or even the workers are asked to check the various lines)

About variable and fixed part of energy consumption, it can be said that a certain amount of energy is consumed whenever the plant producing or not. This amount is the fix consumption also called “Consumption at zero production”. Then, increasing the production the energy use will follow, showing or less a proportional behaviour.

3.4.4. Step 4: Analysis

In this fourth step the losses are classified to isolate the problem i.e. the source of inefficiency. Then it follows the Cost Deployment i.e. the main activity done to individuate the losses and allocate the budget to neutralize them.

- Classification between the fixed part and the variable part
- Seven Types of losses
- Utilization situation during breaks (lunch, pause, etc.), between shifts, over nights and on holidays
- Identification problem
- Identification of possible solutions for reduction of energy losses

About this step it is worth to list the 7 types of energy losses represented in Fig.3.3:

Type 1: Losses due to useless consumption

a) Non-productive periods
b) Stand-by
c) Non-necessary users

Type 2: Losses due to over consumption

a) Set point too high
b) Lack of maintenance
c) Equipment not working in design-conditions

Type 3: Losses due to non-optimization

a) Low saturation
b) Over/Under-engineering
c) Obsolescence

<u>Type 4: Losses due to not using recoverable energy</u>

a) <u>Residual thermal energy</u>
b) Residual kinetic energy

Type 5: Transmission losses

a) Leakages
b) Low insulation
c) Dispersions

Type 6: Transformation losses

a) Technical efficiency

<u>Type 7: More efficient / convenient / sustainable energy source</u>

a) <u>Photovoltaic</u>
b) Geothermal
c) Cogeneration
d) Solar Energy
e) Others

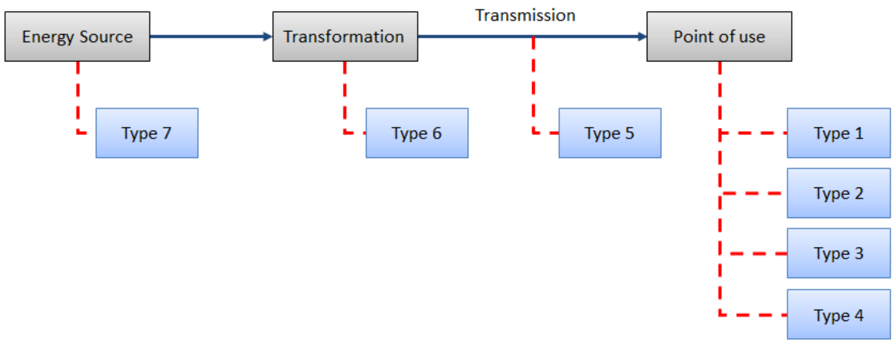


Figure 3.3 - Allocation of the 7 losses in the energy carrier transformation of Fig.2

As stated before, these types of losses are not all relevant for the present document. In fact, mostly of the projects will be developed to neutralize the Type 7 and 4 leaving few spaces to the others. Moreover, for this reason the Cost Deployment activity will not be accurately done for all the process where instead, the WCM methodology advice.

3.4.5. Step 5: Countermeasures

From this point on, the appropriate countermeasures to neutralize the source of losses are developed. The classification of the energy losses done in the step 4 now shows its potential:

- Development of the system of stopping the equipment in case of no production (Type 1 energy losses)
- Countermeasures to make energy consumption of the fixed part to be proportional to the production. Reduction of the fixed part itself (Type 2)
- Optimization of energy consumption (Type 3)
- <u>Pursuit of recovery of energy (Type 4)</u>
- Countermeasures against various types of leakage (Type 5)
- Efficiency improvement by better technologies (Type 6)
- <u>Reduction of electricity consumption using renewable energy sources (Type 7)</u>

Due to the nature of the project the countermeasure taken will attack the losses of Type 7 and 4. The methodology recommends a careful evaluation of B/C when it comes to investment of better technologies, to understand if the action to be undertaken is rentable or not.

3.4.6. Step 6: Standardization

The step 6 is useful to standardize the project developed creating, accordingly to the WCM criteria, the "Energy management book of standard guidelines" available for the group, where are reported all the Best Practices i.e. the most successful projects performed. This archive is useful because the factory is part of a multinational company, so it has various plants all around the world that do has well the same product, so a project applied in one place can be standardized ad repeated in all of them, if valid.

3.4.7. Step 7: Horizontal Expansion

As highlighted in step 6 this last step is the process of repetition of a project that has shown good economic results, from one to all the equipment of the same type in the building.

4. The first 4 Steps

To make this document compact the first four steps will be regrouped in one chapter, developing in the various sections and paragraphs the main activity of them. Despite the rigorous following of the WCM methodology, for the sake of a better reading, the steps won't be all reported in sequence.

4.1. Team formation

The team structure can be briefly introduced saying that there are 3 levels in the pyramid: Pillar Leader, that is the main responsible for the energy department, Specialists, that are the people working for the department and Team Members, that are people with a support role also working in other departments.

The tool used to evaluate the competences of the people in the team is the Radar Chart represented in Fig.4.1. It has the function of visualizing the results of the individual competency evaluation process showing the original level, actual level and required level of knowledge to determine training and/or development plans to close the gaps.

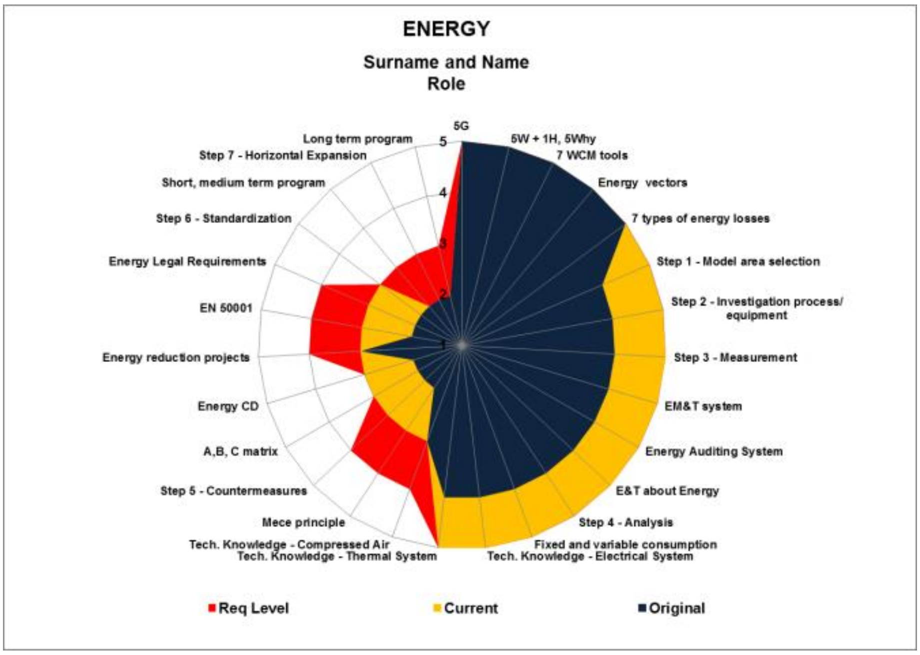


Figure 4.1 - Radar chart

4.2. Energy consumption

As already said, there are two carriers which consumption correspond to an energy expenditure, i.e. electricity and natural gas. In this section the expenditures and the quantities of them will be reported for the 2017, to make an energy image of the factory in that year. Before going to list these expenditures having a look to the Fig.4.2 helps to individuate the order of magnitude.

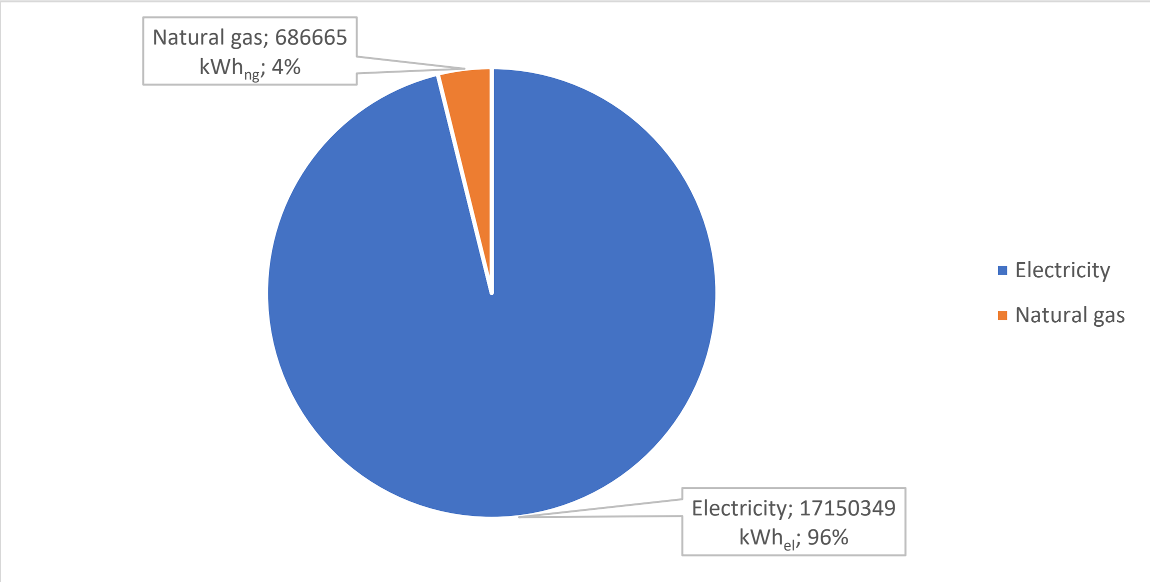


Figure 4.2 - Pie chart of the two energy form consumed as primary sources

4.2.1. Electricity consumption

The electricity consumed by the company is billed in the free market in high tension. The bills in this kind of market consist of two terms which are the power term (PT), that depends on the power contracted, and the energy term (ET) that depends on the consumption of energy. Additionally, two complement fees are added i.e. the excess of power complement (a penalty to exceed the contracted power) and the excess of reactive energy consumption. The other fees like the tax on electricity, won't be considerate in this study.

Before to list the consumption and the cost it is useful to look at the Tab.4.1 that shows how this billing system divide the electricity consumption in 6 periods (P1-6) between the hours of a day.

Month/Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
JAN	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
FEB	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
MAR	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
ABR	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
MAY	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
JUN (1-15)	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
JUN (16-30)	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
JUL	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
AUG	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
SEP	P6	P6	P6	P6	P6	P6	P6	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
OCT	P6	P6	P6	P6	P6	P6	P6	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
NOV	P6	P6	P6	P6	P6	P6	P6	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
DEC	P6	P6	P6	P6	P6	P6	P6	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2

Table 4.1 - Electricity billing period division

The hour in the day in which the electricity is purchased in the market could be either an on-peak or off-peak hour. The electricity consumed in the off-peak time will always be cheaper than the one consumed in the peak time because the demand in the day time is higher than in the night time. The prices of each period for the electricity purchased (ET) and for the power contracted (PT) can be viewed in the following Tab.4.2:

	P1	P2	P3	P4	P5	P6
TE cost [€/kWh$_{el}$]	0,09515	0,08348	0,07177	0,06405	0,05804	0,04684
Contracted power [kW$_{el}$]	2.500	2.500	2.500	2.500	2.500	2.500
TP cost [€/kW$_{el}$]	39,13943	19,58665	14,33418	14,33418	14,33418	6,54018

Table 4.2 - Cost of electricity (ET), power contracted, and cost of the power contracted (PT) for each of the six periods

So, the annual power term will be the resultant sum of multiplying the power contracted in each of the 6 periods by the corresponding power term according to the following formula:

$$PT = \sum_{i=1}^{6} TPcost_i \, P_{c,i}$$

Where, P_c is the power contracted in the tariff period expressed in kW$_{el}$ and TPcoost is the PT price of the tariff period expressed in €/kW$_{el}$/year.

Instead, the ET invoicing the consumption of active energy will be the resultant sum of multiplying the energy consumed in each tariff period for the corresponding ET price in accordance with the following formula

$$ET = \sum_{i=1}^{6} TEcost_i \; Econsumed_i$$

Where Econsumed is the energy consumed in the tariff period expressed in kWh$_{el}$, and $TEcost$ is the ET price of the tariff period considered.

In the following Tab.4.3 are reported the results of these first two terms:

	P1 [kWh$_{el}$]	P2 [kWh$_{el}$]	P3 [kWh$_{el}$]	P4 [kWh$_{el}$]	P5 [kWh$_{el}$]	P6 [kWh$_{el}$]	**TOT [kWh$_{el}$]**	TE [€]	TP [€]
JAN	317.599	522.853				753.279	1.481.620	109.146,50	22.556,00
FEB	304.583	508.254				777.871	1.478.810	107.841,10	22.556,00
MAR			355.064	588.166		844.787	1.662.239	102.718,92	22.556,00
ABR					744.716	806.698	1.442.280	81.006,51	22.556,00
MAY					946.995	838.672	1.660.054	94.244,69	22.556,00
JUN	228.370	209.615	191.478	302.843		721.320	1.537.302	106.149,22	22.556,00
JUL	453.919	421.964				742.149	1.504.212	113.173,59	22.556,00
AUG						882.925	820.816	41.351,79	22.556,00
SEP			298.229	494.568		711.789	1.398.746	86.416,22	22.556,00
OCT					818.373	805.304	1.509.459	85.216,42	22.556,00
NOV			305.938	522.426		800.875	1.514.630	92.926,10	22.556,00
DEC	204.821	340.420				681.216	1.140.182	79.811,32	22.556,00
TOT	1.509.292	2.003.106	1.150.709	1.908.003	2.510.084	9.366.885	17.150.349	1.100.002,38	270.671,98
	8.80%	11.68%	6.71%	11.13%	14.64%	54.62%			

Table 4.3 - Electricity consumed and its cost in the 2017 for each period and in total.

To the two terms (TP and TE) the complement fees, i.e. the excess of power and of reactive energy, are added.

The excess of power is the complement for charging the difference between the power contracted and the power really demanded in any of the periods and it is given by the following formula:

$$PTexcess = \sum_{i=1}^{6} K_i \; 1.4064 \; A_{ei}$$

Where K_i are coefficients that will assume different values according to the tariff period I as in the following Tab.4.3:

	P1	P2	P3	P4	P5	P6
Excessive power cost c€ /kW	1	0,5	0,37	0,37	0,37	0,17

Table 4.4 - Cost of the excessive power consumed for each period

And A_{ei} is calculated according to the following formula:

$$A_{ei} = \sqrt{\sum_{i=1}^{6} (P_{e,i} - P_{c,i})^2}$$

Where $P_{e,i}$ is the power demanded in each quarter of the time and in which it is exceeding the contracted power $P_{c,i}$.

The excess of reactive energy instead, will be applied on all the tariff periods except for the P6, if the consumption of reactive energy exceeds 33% of the active consumption during the billing period considered cosφ<0,95. The Ann.1 reports the price paid in the 2017 for these two excesses.

The electricity is employed in the plant to supply:

- Emf processes (basically all the production machines need this kind of energy)
- Compressors
- Lighting (offices and plant)
- Water cooling (for the injectors machines)
- HVAC (offices and plant)

Their respective consumes are reported in the following Tab.4.5:

	Energy consumed [kWh_{el}]	Expenditure (only ET) [€]
EMF PROC	12.292.113	732.940,59
COMPR AIR	1.380.460	82.312,54
LIGHTNING	1.358.908	81.027,45
COOLED WATER	1.123.158	66.970,45
HVAC	995.711	59.371,13
TOT	17.150.349	1.022.622,16

Table 4.5 - Energy consumption divided for point of use activity, and its relative cost

So, the relative Pareto graph is the one reported in Fig.4.3 below:

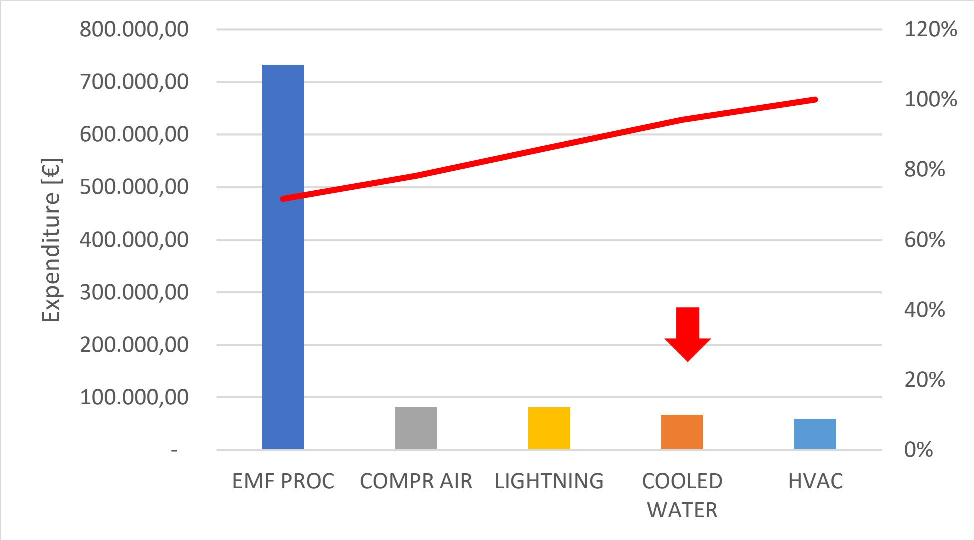


Figure 4.3 - Expenditure divided by the type of transformation that the electric energy does for the point of use (refer to Fig.2)

The projects that will be studied in this thesis will affect the chilled water electricity cost, so already from this point the Model Area starts to define. In fact, from now on, the reader will notice that the focus will be on the water cooling process that will be deepen more than the other processes to lay the foundations of the projects. The reasons of this selection, apart from being a large part of the expense of the annual electricity bill, were due to the opportunities encountered during the permanence of the writer in the factory.

It should be clarified that for the WCM method the Model Area selection philosophy consist in focusing the people efforts in one area of the plant, to develop methods, projects and ideas that can be expanded subsequently in all the areas. For the ambit of this study instead the focus will be mostly on the engineering aspect.

4.2.2. Natural Gas consumption

For the natural gas the billing follows the free market system. It consists in tariff with a binomial structure i.e. it is composed by two terms, one fixed billing term and one variable function of the gas consumed:

$$Bill\ [€] = Fixed\ term\ [€] + Gas\ consumed\ [kWh_{ng}] \cdot Variable\ term\ [€/kWh_{ng}]$$

Moreover, to this bill other terms are added such as the equipment's rental and the IVA that for the sake of simplicity won't be considered in this study.

The method of billing the fixed term varies according to the group of consumers to which it belongs according to the pressure level of the gas pipelines to which it is connected.

	FIXED	VARIABLE			OTHER	TOT	
Month	Amount [€]	Gas consumed [kWh_{ng}]	Unit price [€/kWh_{ng}]	Amount [€]	Equipment renting [€]	Amount (without IVA) [€]	Unit price [€/kWh_{ng}]
JAN	570,05	243.611	0,0242	5.899,78	0	64.69,83	0,0266
FEB	570,05	46.111	0,0242	1.116,72	0	1.686,77	0,0366
MAR	565,65	13.333	0,0242	322,91	98,86	987,42	0,0741
ABR	477,35	12.222	0,0257	314,64	98,71	890,7	0,0729
MAY	311,8	2.500	0,0257	64,36	197,42	573,58	0,2294
JUN	275,5	1.944	0,0257	50,06	98,71	424,27	0,2182
JUL	275,5	1.944	0,0273	53,06	0	328,56	0,1690
AUG	275,5	833	0,0273	22,74	0	298,24	0,3579
SEP	275,5	1.667	0,0273	45,48	197,42	518,4	0,3110
OCT	275,5	1.944	0,0273	53,06	98,71	427,27	0,2197
NOV	328,16	158.889	0,0271	4.307,8	0	4.635,96	0,0292
DEC	570,05	201.667	0,0233	4.690,17	0	5.260,22	0,0261
TOT	4.770,61	686.665	-	16.940,78	789,83	22.501,22	-

Table 4.6 - Billing of natural gas for the 2017

This resource is used in the plant for the thermal energy production to be supplied to the ovens or to heat the rooms (HVAC) using radiant and infrared tubes as it can be seen in the following Tab.4.6:

	Energy consumed [kWh_{ng}]	Expenditure [€]
HVAC	411.999	10.164,47
OVENS	274.666	6.776,31
	686.665	16.940,78

Table 4.7 - Energy consumption in the form of natural gas divided for point of use activity, and its relative cost

The Pareto graph of the gas consumption is so reported in the following Fig.4.4:

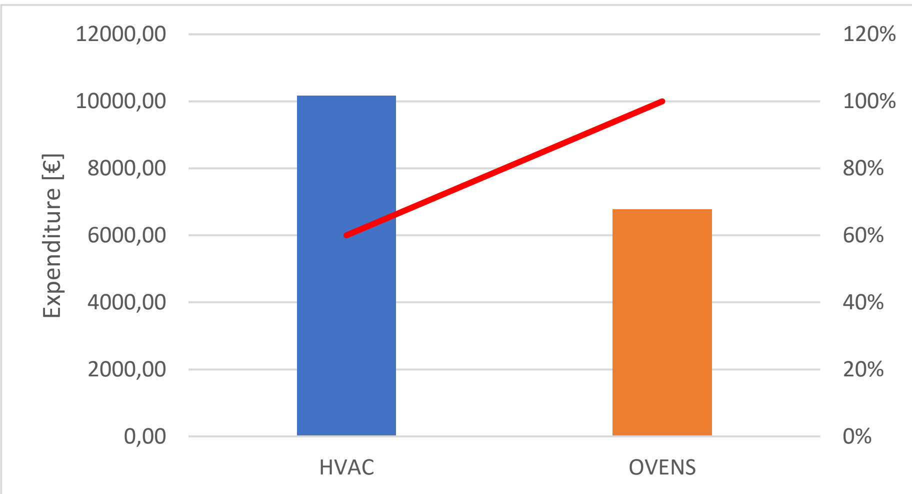


Figure 4.4 - Expenditure divided by the type of transformation that the gas energy does for the point of use (refer to Fig.2)

Where the HVAC consume around the 60% of the resource and the ovens in the montage zones the rest 40%. The following paragraph will explain these machines.

4.3. Machinery inventory & analysis

Before the description of all the technologies present in the factory it is interesting to consider the Tab.4.8 in which are reported the magnitudes of the powers installed in each area divided by activity. To note that he injection areas (A1 and A3) are the ones with the highest powers installed, with a 48% with respect to the total. Instead, talking about process the emf processes are the ones with the biggest power installed (60%), followed by the water cooling (15%).

	Power installed [kW]						
Area	EMF PROCESS	LIGHTNING	HVAC	WATER COOLING	COMPR		
A1+A3	959	25	2	468		1454	48%
A2	4	22	30	0		55	2%
A4	229.3	2	29	0	78	339	11%
A5	102	35	58	0	78	273	9%
A6	175	24	58	0	78	334	11%
A7	136	21	58	0		215	7%
A8		11	5	0		17	1%
A9	229	18	29	0		276	9%
A10		57	30	0		87	3%
TOT	1834	214	301	468	234		
%	60%	7%	10%	15%	8%		
SUM	3051						

Table 4.8 - Power installed divided per area

As said in the end of the paragraph 4.2.1. this study will focus on the water cooling process that take part for the injection area (A1+A3) that is therefore the Model Area.

4.3.1. Emf process

Electromotive force is the difference in the electric tension between two points that causes an electric current to flow into a circuit, this current then is converted in mechanical or thermal energy which permits the processes in the machines.

Despite being the part that consumes the most, none of the projects of this study will be implemented to any of the machines in term of reduction of electromotive force. So, the technologies proper of this activity will be just briefly introduced.

As it can be seen in Tab.4.8 the zones A8 and A10 don't exploit this kind of energy carrier, this is because they include the warehouses, the offices and the exterior place, all areas in which no production machines are present. Instead the zone A4 present a little power installed, which is the one of few machines utilized for testing the final product that will not be deepen because not interesting for this study.

The biggest electromotive power installed is the one of the injection zones (A1 and A3). It is needed to activate all the 31 injection molding machines for plastic pieces creation. These devices present a range of nominal power that goes from a minimum of 17.71 kW_{el} till a maximum of 59.11 kW_{el}. They are all of the horizontal type and they are composed from two parts i.e. the injection unit and the clamping unit. The form of the plastic pieces that can be obtained depend on the mold used inside. An important part of their consumption is given by the heaters for reaching the plastic melting temperature. They must be electrical because the temperature control during the moulding process impact the quality of the final product.

As explained in the production paragraph, after the molding there is the metallization of the parts and it is done in the homonym areas i.e. A4 and A9. These two areas are equal each other because they present 4 machines each, everyone with a nominal power of 57.2 kW_{el}. These machines are of vacuum metalizing type, its working principle is based on letting the aluminium evaporating inside a vacuum chamber to deposit it on the plastic pieces surfaces to form a reflective coating.

The rest of emf processes consume energy in all the assembly lines which present various type of industrial machines, not interesting to be explained given the focus of the project.

4.3.2. Compressors

In most industries, compressed air is involved in production to automate and accelerate the processes.

In the factory are in function 3 Rollair RLR 100 each one of a nominal power of 75 kW_{el} for a total nominal power installed of 225 kW_{el} (the technical characteristics are in the Ann.2). Moreover, to support them also 3 equal air dryers of 2.77 kW_{el} are present. They have the function of removing water vapour from the air to avoid operational problems.

The operation of these machines is the following: firstly, is started the compressor 1 with a frequency variator. When the compressed air demand of the installations increases and just one compressor is not able to supply it, also the compressor 2 is put in operation. The same happen with the last compressor and all of them have been chosen to satisfy the maximum possible demand of the plant. They generate a compressed air at a pressure of 8 bars.

But there is a relevant problem when analysing the thermodynamic of these devices. In fact, the Sankey diagram in Fig.4.5 shows that their efficiencies are in general very low i.e. only the 4% of the electrical power supplied to the process is transformed in compressed air, because the most of it, around the 90%, is dissipated in heat (loss of the Type 4a) [2]. Due to this fact is usual to install a system to recuperate part of this heat for building or industrial applications. For the compressors employed in the factory this system is already integrated [3], so no extra costs are needed to modify the machine avoiding also efficiency and reliability problems that could occur in the modification.

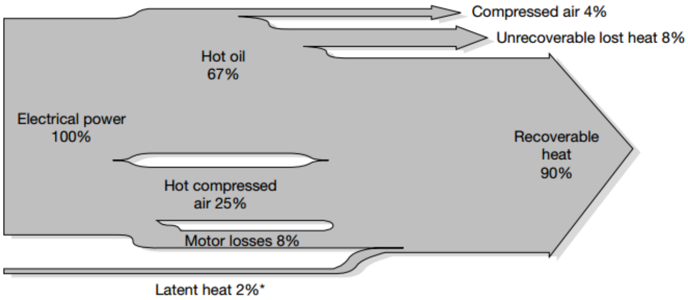


Figure 4.5 - Sankey diagram of a generic air compressor (the percentage are not referred to the machines installed in the factory, they are just indicative to have an order of magnitude of the energy transformations)

The Rollair [3] is an oil-injected screw compressor, that use oil to cool down the air that is compressed by the screw elements. This mean that the oil is directly injected in the elements to mix with the air and due to the direct contact, an important part of the heat that the air has gained during the compression, is transferred to the oil. The oil has also a lubricating task. Then, the air needs to be separated from the oil before its distribution and this is done in the oil separator vessel that collect all the hot oil (can reach 120°C) to be send in the oil cooler to cool down before repeating the process. The air separated by the oil is still hot (about 80°C) and before to be used it needs to pass in another cooling unit called aftercooler, that bring it to 25÷40°C [4].

The compressors like the Rollair that has a heat recuperation system integrated, to cool down the hot oil utilize both the standard cooling system, i.e. a radial fan (Heat exchanger 1 in Fig.4.6), and an oil-water heat exchanger (Heat exchanger 2 in Fig.4.6), that is in charge to transfer the heat to a flux of water that becomes the fluid transport media to recover the oil temperature. This system is regulated automatically by means of a thermostatic valve, and in case of limited water cooling capacity (periods of low heat sink, i.e. when no heat recovery is needed), the standard cooling system, as to say the radial fan, will operate and backup the energy recovery device.

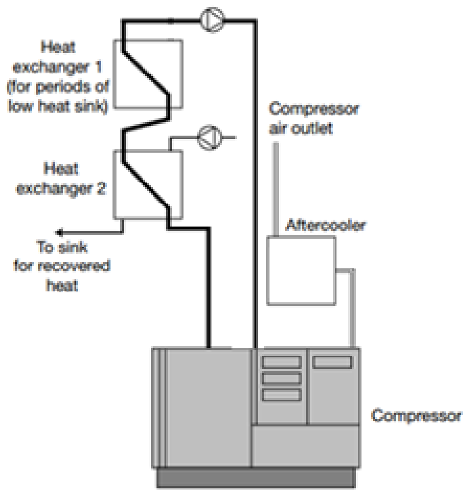


Figure 4.6 - Scheme of the cooling circuit of the air compressor in study. The oil cooler unit is composed by heat exchanger 1 and 2. [2]

This means that the heat can be recuperated only by the hot oil (not by hot compressed air) and from the technical specification the maximum heat that can be recuperated is the 75% of the total electrical energy consumption. But this maximum corresponds with the heat that can be recuperated cooling down the oil from 100°C, that is the oil temperature exiting the screw compressor, to 60°C that is the oil temperature to be injected inside the screw compressor. For this case instead, the absorption chiller works at nominal temperatures between 95 and 80°C so the heat recuperation will be lower than the 75%. To calculate it is firstly needed to calculate the oil flow rate circulating the compressor, this is done with an energy balance in the oil circuit assuming no heat losses and a specific heat of the oil about 2 kJ/kg/K:

$$m_{oil} = \frac{Qoil}{c_{oil}\,(100°C - 60°C)} = \frac{75\;kW \cdot 75\%}{2{,}0\,\frac{kJ}{kgK} \cdot (100°C - 60°C)} = 0{,}70\,\frac{kg}{s}$$

In the case of no heat recovery all the oil heat (Qoil) will be dissipated by the radial fan. On the other hand, in the case of heat recovery for the absorption chiller, part of this heat will be absorbed by the water (between the temperatures of 95 and 80°C) and just the other part will be dissipated by the radial fan to bring the oil to 60°C. So, the heat that can be recovered for the absorption chiller is:

$$Q = m_{oil}\,c_{oil}\,(100°C - 85°C) = 21\;kW$$

That is the 28% of the total electrical consumption. The temperatures are taken assuming a ΔT_{ml} of 5°C in the oil-water heat exchanger.

A last observation useful for the simulations is that the compressors are located inside a power house, so the oil operating temperatures can be assumed constant through the year.

4.3.3. Lightning

The lightning power installed in each area is reported in the Tab.4.8. Moreover, the Ann.2 contains the inventory of all the lamps installed in the building considering the type of device, the luminaries' number and so the various powers consumed. It contains also the hours of use in the year to estimate the annual electric consumption.

Considering the control of this lightning system instead, it can be said that in most of the rooms the ignition and the shutdown regulation is manual by means of magnetothermal switches in the main production area and for simple switches in the smaller rooms. For those areas such as warehouses, where the occupation is low, there are none type of sectorization or control as presence detectors. So, these areas remain bright even though there are no staff working there, implying a waste of electricity of the Type 1. A possible countermeasure could be the installation of presence detectors.

4.3.4. Water cooling

Like any installation that employ plastic injector machines, the plant in object uses water cooling units. These devices are called chillers and they are responsible of keeping the temperature of a closed water circuit (that cool down the injection machines) within default values. This water circuit supplies each machine to refrigerate in turn, the hydraulic oil, responsible of the lubrification of all the mechanical moving parts. In fact, they have installed a special control unit that turn off the machine if the oil temperature exceeds the 20°C, to avoid breakdowns of the mechanical components.

The electric power consumed by these devices is important due to the large volume of the water to be refrigerated. In fact, the injection areas (A1 and A3) are supplied by cold water refrigerated by 3 equal chillers Carrier 30GK 100 for a total maximum nominal refrigeration power of 975 kW_{th} that correspond to almost half electrical MW installed (468 kW_{el}).

For the nature of the project studied, it is useful to investigate the functioning of the actual cooling water system. which scheme is represented in Fig.4.7.

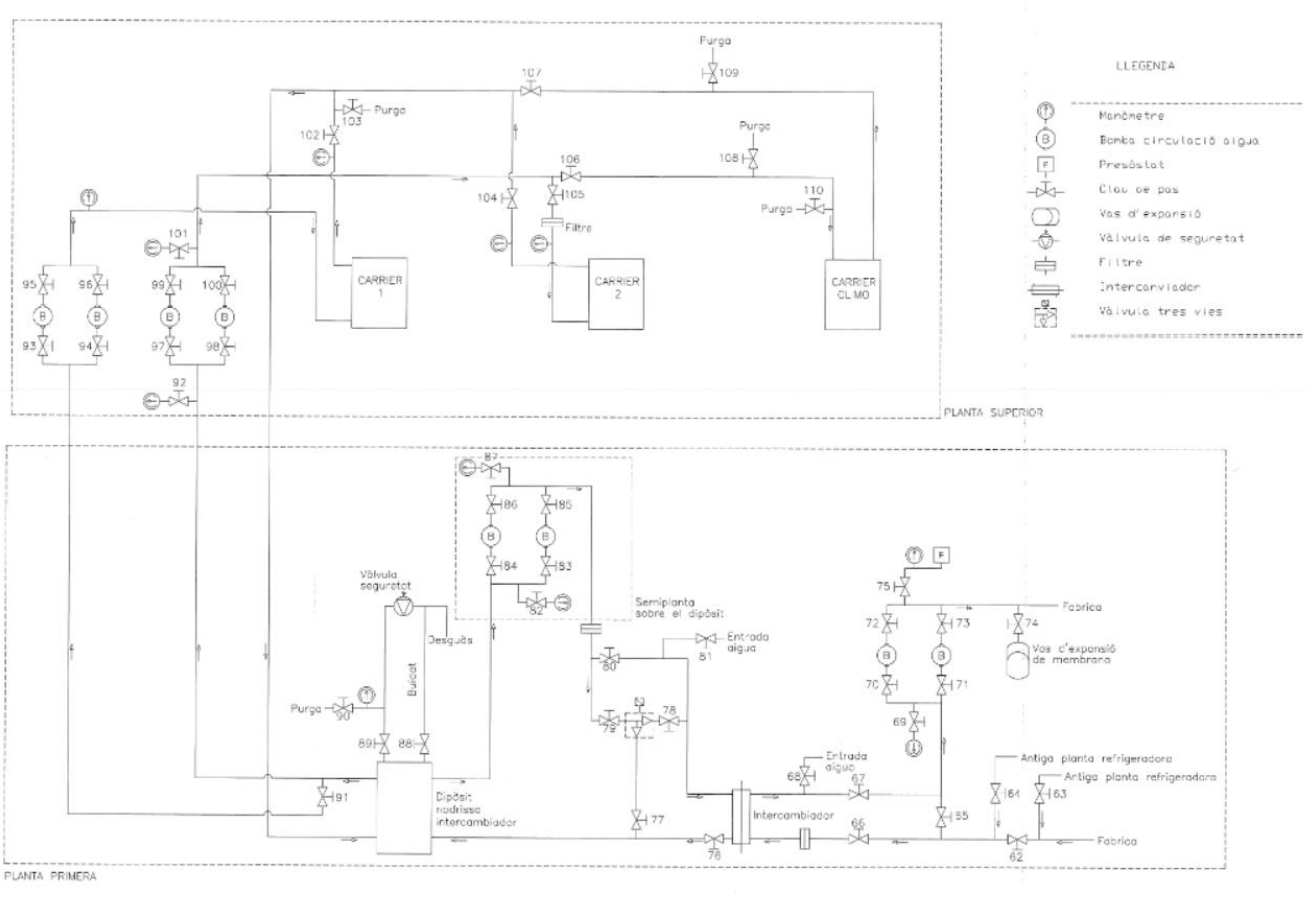


Figure 4.7 - Present water cooling system scheme

The Carrier chillers perform a vapor compression cycle utilizing the refrigerant R-407C as working fluid. Their condensation temperature is not variable but fixed around 20°C above the maximum yearly temperature i.e. to 50°C. The fact that this temperature is not variable with the ambient one implies a loss of the Type 3b (Over/Under-engineering) estimated, by another study done in the past, to be 25,4% of the electric consumption.

Their COP can be calculated from the plate values as follow:

$$COP = \frac{Q}{W} = \frac{325\ kWth}{156\ kW} = 2{,}08$$

But, to obtain the refrigeration power from the electric power consumption in the next section 4.4., it is useful to study how this coefficient varies with the ambient temperature.

In fact, being air-cooled chillers, the work W in the formula is composed by the compression work W_{compr} that is constant due to the fixed condensing temperature and by the work of the fans W_{fan} that are the devices necessary to exchange the condensing power with the ambient, blowing air to the condenser:

$$COP = \frac{Q}{W_{compr} + W_{fan}}$$

The electrical power consumed by the fan can be approximated with a cubic trend as Mazzarella L. [5] suggest:

$$W_{fan} \cong k\, V^3 \ \ with\, V\, as\, the\, air\, flow\, rate\, in\ \frac{m^3}{h}$$

The constant k is founded using the nominal air flow rate in the brochure and the maximum fan power (there are 4 fans, each one with a maximum power of 4,8 kW_{el}) as following:

$$k = \frac{W_{fan}}{V^3} = \frac{19{,}20\ kW}{(21{,}11\frac{m^3}{s})^3} = 0{,}0019$$

So, being the outside temperature low there will be a low or even null need of those fan. In the other hand being the ambient temperature high, there will be the full need of their convective heat transfer effect, implying a non-negligible consumption of power and so a variation of the COP. To find a correlation between the COP and the outside ambient temperature it is needed that volume flow rate of air. To find it the condensation power is firstly calculated from the refrigeration cycle balance using the nominal values from the technical characteristics in the brochure (Ann.4) as following:

$$Q_{cond} = Q_{refr} + W_{compr} = 325\ kW + 130\ kW = 455\ kW$$

Then the volume flow rate is founded from the mass flow rate that is in turn calculated from the energy balance at the condenser for each ambient temperature:

$$V = \frac{m}{\rho_{air}} = \frac{Q_{cond}}{C_{p,air}(T_{cond} - T_{amb})\rho_{air}}$$

Finally, its values are used to calculate the electrical power of the fan with the cubic correlation and so the COP. To have a correlation for transform the electrical power of the chillers in refrigeration power a 3rd order polynomial interpolation is used:

$$COP = -2 \times 10^{-5}\, T_{amb}{}^{3} + 0{,}0006\, T_{amb}{}^{2} - 0{,}0068\, T_{amb} + 2{,}5003$$

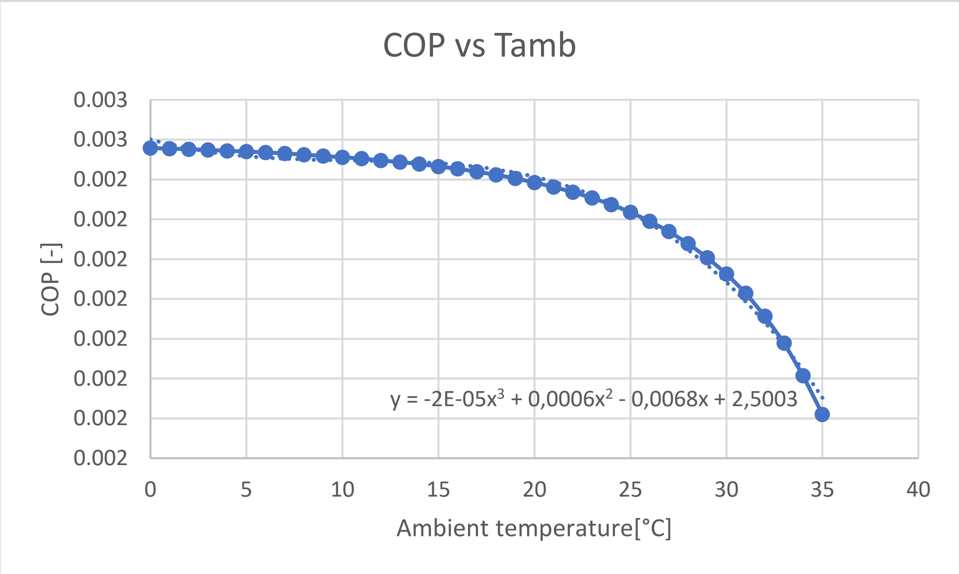


Figure 4.8 - COP in function of the environment temperature. The dotted line is the polynomial interpolation employed in the hourly simulations.

The 3 machines are positioned in parallel to refrigerate the first water circuit that in turn refrigerate the closed one that go to the fabric i.e. to supply the injectors machines as it will be clarified in the following rows. To feed them with the water there are 2 systems of a couple of redundant pumps, one feeds only the chiller 1 and the other feeds the remaining chillers 2 & 3. This design is thought to utilize the chiller 3 only in extreme cases of high demand as it is for the compressors, when the first 2 machines are not enough or when one of them fail and need maintenance. The valves are closed or open in function of the need.

The water cooled in the chillers is sent to a deposit with a function of thermal inertia (keep better the steady state conditions) and pressure compensator (equalize the different pressures of the supply fluxes). Another system with a couple of redundant pumps send this water to the heat exchanger that refrigerate the closed circuit, the one in charge of keeping the injectors machines in the temperatures limit.

The chillers are set to operate between 8 and 11°C. In the reality the temperatures oscillate around the set values and the assigned workers annotate the real working temperature to detect malfunctioning. Instead the closed circuit that goes in the factory works between 14 and 19°C. These are the temperatures that dictate the operating conditions of the heat exchanger (Sedical UFP-102, 700 kW_{th}).

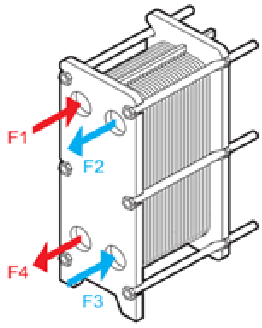


Figure 4.9 - Heat exchanger counter-current configuration. F1=19°C, F2=11°C, F3=8°C, F4=14°C

This system is in operation since many years. This imply significant losses of the Type 5a/c due to the fouling of the heat exchanger and of the tubes and of the Type 5b due to the obsolete insulation technology.

4.3.5. HVAC

This study will not affect the climatization system of the building, so for sake of simplicity it won't be deepen. It can just be said that correspond to 301 kW_{el} of power installed and if the reader is interested the table in the Ann.6 reports its components for the ventilation and air conditioning parts, instead the heating is part of the next paragraph.

4.3.6. Thermal energy generation

The technologies of this paragraph are the ones that burn the totality of the gas mentioned in the paragraph 4.2.2.

In the installations of the plant radiant tubes are used for the heating of the production areas. Two kinds of models are employed: 2 modules of radiant tubes (GIRAD model) and 10 radiant screens of smaller length (PANRAD model).

Their principle is the same: to make circulate in depression air and combustion gases reheated inside a tube, reaching a surface temperature of a range in between 100 and 300ºC. At these temperatures the material emits in the infrared spectrum and, by means of reflectors, radiates the zone of work. It is a technology designed for large surfaces air conditioning, especially for large height. The combustion units have a thermal performance of more than 92%, and the thermal power is of 40 kW_{ng} for PANRAD and 300 kW_{ng} models for GIRAD models.

All the rest gas consumed is employed by the ovens utilized in the montage zones A5, A6 and A7.

4.3.7. Transformers

The electrical installation has 4 transformers between 800 kVA and 1,600 kVA. Three of them are in the area where the air compressors are placed, and the other one (Transformer 1) is in the area A7. Their characteristics are listed in the Ann.5 and their function is to transform the high tension of the electricity supply from the national grid in medium and low tension utilized in the plant.

4.3.8. Condensers

For reactive energy compensation there are 3 condenser batteries of 1940 kVAr in total. The characteristics of these are listed in the Ann.5. These devices are the ones in charge to avoid the reactive energy penalties briefly introduced in the 4.2.1. paragraph.

4.4. Model Area measurements

To complete the analyzation of the chilled water refrigeration system it is useful to observe its load, i.e. the demand of refrigeration power needed over a certain time step discretization. To obtain it the energy measurement system is employed. It measures the electric consumption of the 3 chillers that is therefore converted in refrigeration power using the COP.

4.4.1. Measurement system

An energy management system aims to measure and record all the electrical parameters of the machines installed in the factory for its subsequent treatment. With this it can be seen what it is consumed, where it is consumed and at what moment it is consumed. This is achieved installing network analysers at the critical points of consumption.

The system can be used to:

- Determine economically the expected savings of an energy project (this is the case of how it is employed in this paper)
- Preventive maintenance of electrical lines and installations
- Imputation of departmental costs or of productive processes
- Give alarms against excessive consumption, malfunctioning of technical installations (e.g. capacitor batteries)
- Monitor the reactive power consumption

To achieve these objectives, and due to the large volume of information that each of the measurement centres provide, it is necessary to have a centralized data collection system, software or control application. The purpose of this software is data processing and reporting, with the aim of adopting preventive or corrective measures to the installation. For the purposes set forth, Circutor has developed the integral energy management software called Power Studio Scada that is the software utilized in the factory.

The Circutor network analysers are of the CVM series. They are suitable for the control and supervision of the main electrical parameters in single-phase and/or three-phase networks, of three or four threads in low and medium tension. The measurement is carried out in True Effective Value (TRMS). The effective value is the square root of the average of the square of alternating current or voltage values. These analysers register the active, reactive inductive, reactive capacitive and apparent energy for each of the programmed periods.

The network analysers installed in the electric chillers of the chilled water system are of the type CVM MINI. They have the following function:

- Three-phase
- True effective value
- Maturation on 4 quadrants
- Maximum demand calculation
- Neutral current calculation
- Total harmonic distortion

The CVM network analysers are communicable among them using the standard RS485 protocol. The subsequent connection to a PC can be done via a RS485-RS232 converter directly on the PC serial port or via a TCP-RS485 converter connecting the computers to the local network, as shown in the following Fig.4.10:

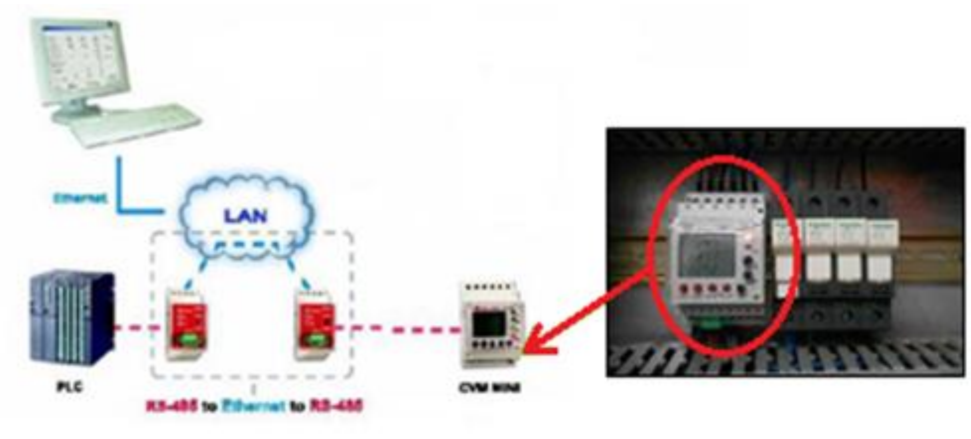


Figure 4.10 - Connection of the CVM network analysers to the network

4.4.2. Refrigeration load measured

The devices exposed in the previous section were installed to the 3 electrical chillers of the water cooling system to obtain the electrical power consumption of these machines that is in turn, if multiplicated by the COP, the power exchanged at the heat exchanger, so the refrigeration power needed to cool down the water of the closed circuit that goes in the factory to refrigerate the injection machines without considering the losses.

The measurement campaign started January 1st of 2017 at 00:00 and end the December 10th of 2017 a 23:00. The time step selected was of an hour. For simplify the load just a week for each month was measured and replicated for all the month. The devices measure the voltages and the currents of the triphasic electric devices, then from these values it calculates the total active power, that is the sum of the 3 powers of the singular phases multiplicated for the power factor:

$$Pi = 3\,P_{ph,i} = 3\,V_{ph,i}\,I_{ph,i}\cos\varphi \quad [i = 1,2,3] \qquad where\ \cos\varphi\ is\ the\ power\ factor$$

The measurement system can calculate also the reactive power and other electrical parameters to monitor the proper functioning of the installations, but for this study the interest is only on the active power because it is needed to find the refrigeration power. So, the active powers extrapolated are 3 and they correspond with the 3 chillers and for the total active power consumed it is simply needed to sum them all as in the following formula:

$$P = P1 + P2 + P3$$

And then multiply it by the chillers COP function of the ambient temperature (the hourly temperature comes from the PSOL software utilized for the photovoltaic system configuration) as studied in the paragraph 4.3.4. as following:

$$P_{refr} = P_{el}\,COP(T_{amb})\ \forall\ hour$$

About the refrigeration load founded the following Fig.4.9 report the average, maximum and minimum as well as the average daily energy needed:

	REFRIGERATION NEEDS			
Month	Average hourly power [kW_{th}]	Max. hourly power[kW_{th}]	Min. hourly power [kW_{th}]	Average daily energy [kWh_{th}]
JAN	287	367	178	6891
FEB	274	336	173	6577
MAR	304	448	154	7293
ABR	340	497	208	8155
MAY	348	486	187	8355
JUN	342	508	158	8196
JUL	354	650	167	8489
AGO	345	498	153	8281
SEP	332	491	203	7978
OCT	303	445	153	7271
NOV	285	390	197	6850
DEC	255	313	196	6122

Table 4.9 - Refrigeration load monthly relevant values

Analysing these data is noted is that:

- The load seems to have a periodical behaviour with the maximum values during the day shifts (6:00 to 23:00) and the minimum values during the night shifts (23:00 to 6:00). Moreover, this power is lower during the week-ends due to the lower production volume. It is worth to clarify that in the Sundays the assembly lines are stopped because they need a lot of personal, but there are some injection machines, so called "tense flow", that can work uninterruptedly without the presence of so many workers and that is the reason why there is still an important chilled water need.
- The load in December is at the minimum average i.e. 255 kW_{th} with peaks around 313 kW_{th} (Fig.4.11), instead in July is at the maximum average as to say 354 kW_{th} with peaks around 650 kW_{th} (Fig.4.11). These two months can be seen respectively as the best case and worst case i.e. the month with the minimum and the maximum energy needs. This fact is due to the ambient temperature that when for example in summer is higher imply heat infiltrations and so a higher refrigeration power needed to cool down the water at the desired temperature. In fact, the injection areas (A1 & A3) are not air conditioned as the assembly areas or the offices, because they present less personal and so the temperatures are similar to the external ones.
- The behaviour of the load, that in July present more peaks while in December is flatter (Fig.4.11) is maybe due to the production volume. However, this aspect is not considered in this study.
- The absolute peak is registered in the worst case month of July and is of 650 $kW_{th.}$ This value is lower than the total refrigeration power installed of the chiller of 975 kW_{th}, because one of them, as said in the relative section (4.3.4.), has just the function of back up, i.e. it has to work when the other two are under maintenance. In the reality all of them are always functioning at a power lower than the nominal one but is common to turn off one of them for the maintenance and so the other two must be able to supply the total load.
- The total refrigeration energy needed for the year 2017 is of 2.751.663 $kWh_{th.}$ This correspond to a total electricity consumption of 1.123.158 kWh_{el} and to an average COP of 2,45. The expense is of 66.970,45 € as mentioned on the Tab.4.5.

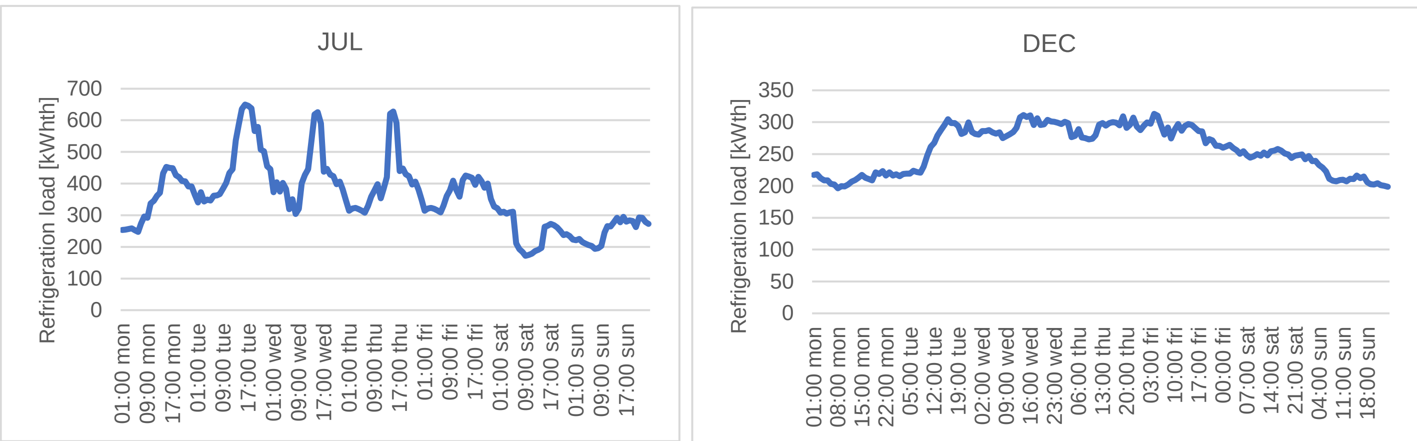


Figure 4.11 - Refrigeration load of July and December

From these 12 weeks measured for each month the load is replicated to build the annual one for dimensioning the new technologies. It is completely reported in the Ann.8.

4.4.3. Compressor power measured

Apart to the chillers the CVM network analysers were installed to other machines in the plant to monitor their working conditions like the compressors. As one of the technologies consists in recuperating their waste heat, it is needed firstly to know their load, i.e. their electricity consumption.

So, during the period from 12th to 17th May 2017 the measurement system, installed in the general switch of the 3 Rollair air compressors of 75 kW_{el} of power each, estimated a consumption, based on the data obtained during those 5 days, of 1.151.590 kWh_{el} per year, 6,7% of the annual electricity consumption, that correspond to an expense of 92.127,00 €.

To reconstruct the yearly load for the dimensioning part, it is observed that:

- The maximum power is 219 kW_{el}, when the nominal power of the three devices is 225 kW_{el}.
- Daily demand is similar in the working days (Monday to Friday), with an average daily consumption of 3.679 kWh_{el}, but very different from the weekend, where consumption is around the half.
- The hourly average power is around 175 kW_{el} in the day shifts of the working days, 87,6 kW_{el} in the night ones. For the week ends instead, it is the half i.e. 88 kW_{el} for the day and 44 kW_{el} for the night.

This shape is due to the volume of production, that as said in the section 3.2., is not the same for all the week long, but in the night shifts (23:00 to 06:00) it is the half of the day shifts (06:00 to 23:00) as for the week end (Saturday and Sunday) that is half of the working days (Monday to Friday). These machines are in fact installed to supply compressed air to the assembly areas (A5/6/7) that adopts the shifts considered.

4.5. Cost Deployment & Clarification of objectives

4.5.1. Clarification of objectives

As exposed in the introduction the scope of this project is the cut of the company electricity needs both by implementing energy efficiency projects and by substituting them by renewable local generation. To verify the success of this objective a KPI will be verified in the conclusions but it is worth to clarify how and to choose a strategy to undertake.

A rough assumption that need to be done is considering the production of the 2017 constant in the future years analysed. This is due to the difficulties of predicting a continuously mutating market, ambit that is far from the field of study of the present thesis. This assumption implies that the pieces produced in the year 2017 will be the same far all the years to come. This is valid though for the GHP, because they depend on the produced pieces and for the refrigeration load, because it is function of the production as well. While consideration on the load will be useful for the economic analysis, the GHP are needed in the calculation of the KPI to be respected for the year 2019 target. It is remembered that the only KPI employed in this paper as said in the introduction is the ratio between the tons of CO2 emitted and Good Hours Produced and for the year 2017 it has been:

$$KPI_{17} = \frac{tnCO2_{17}}{GHP_{17}} = 0{,}0127\frac{tnCO2}{h} \qquad Eq.(1)$$

To find the GHP of the 2017 the reverse formula can be utilized, using the tons of CO2 emitted calculated as following (the emission factors comes from the billing papers reported in the Ann.9 and from [6]):

$$\begin{aligned} tnCO2_{17} &= Electricity\ consumed \cdot EF_{el} + Natural\ gas\ consumed \cdot EF_{ng} \\ &= 17150{,}349\ MWh_{el} \cdot 0{,}34\frac{tnCO2}{MWh_{el}} + 686{,}665\ MWh_{ng} \cdot 0{,}202\frac{tnCO2}{MWh_{ng}} \\ &= 5970\ tnCO2 \end{aligned}$$

So, reversing the Eq.1:

$$GHP_{17} = \frac{tnCO2_{17}}{KPI_{17}} = 470065\ h = GHP_i\ \ with\ \ i = 18, \dots, 38$$

Once found its value the next step is understanding how it is possible to respect the KPI target of 2019. That is only if the following is verified:

$$KPI_{19} < KPI_{19}|_{target} = 0{,}0126\frac{tnCO2}{h}$$

$$\frac{(17150{,}349\ MWh_{el} - X) \cdot 0{,}34\frac{tnCO2}{MWh_{el}} + 686{,}665\ MWh_{ng} \cdot 0{,}202\frac{tnCO2}{MWh_{ng}}}{470065\ h} < 0{,}0126\frac{tnCO2}{h}$$

Assuming a constant production regime also the electricity consumed, and the natural gas burned will be the same through the years, so being the KPI_{17} already higher than the objective of 2019 it is needed to lower either the electricity or the gas value. The project studied is going to impact only in the cut of electricity consumed and it is going to do it of a quantity called X that, from the previous equation, to respect the target must be:

$$X \geq 138\ MWh_{el}\ that\ correspond\ to\ 47\ tn_{CO2}$$

This mean that the electricity consumed by the chilled water system that is 1.123.158 kWh$_{el}$ must be decreased at least of an 12% to respect the target for the 2019.

4.5.2. Cost deployment

If the reader is interested the money losses divided for area, activity and type of losses are reported in the Ann.10.

About the losses of this work the only relevant to mention are the one of the air compressors. Considering its load and the percentage available for the heat recovery they amount to 322.445 kW_{th}/year that is in money assuming to generate it with natural gas:

$$322.455\ \frac{kWh_{th}}{year} \cdot 0{,}0328 \frac{€}{kWh_{ng}} = 10.566{,}48\ €$$

5. Step 5: Countermeasures

In this chapter the Step 5 is undertaken, to develop the countermeasures chosen to neutralize the source of losses and to reach the scope of the work. As anticipated, the main source of losses that will be attacked are of the Type 4a and 7a, so the relative countermeasures are respectively the reduction of electricity consumption recovering the waste thermal energy from the air compressors trough the absorption chiller and the substitution of an amount of the grid electricity needs with the local renewable generation.

Instead the third technology as to say the thermal energy storage will not impact in the cut of the total electricity purchased but will change the time of when it is purchased. In fact, in the off-peak hours, i.e. in the night time, the demand and so the prices are lower. Hence, generating chilled water in the night time to store it when needed implies saving in the electricity bills, but it is also useful at national level because levelling the demand serve to avoid the installation of new capacity.

It may be said that in principle the idea was the project of a solar cooling system, i.e. a solar thermal field to aliment a big absorption chiller supported by a thermal storage. But seen the economic analysis result, that shown a very high cost of the energy generated, the decision was to keep all the 3 technologies and utilize them in different ways.

5.1. Photovoltaic field

5.1.1. Renewable resource

Being the plant located in Spain, between the renewable sources, the solar one was selected, due to its abundance. To have an idea the following Fig.5.1 can be considerate, it shows the monthly radiation on a horizontal plane G(0°):

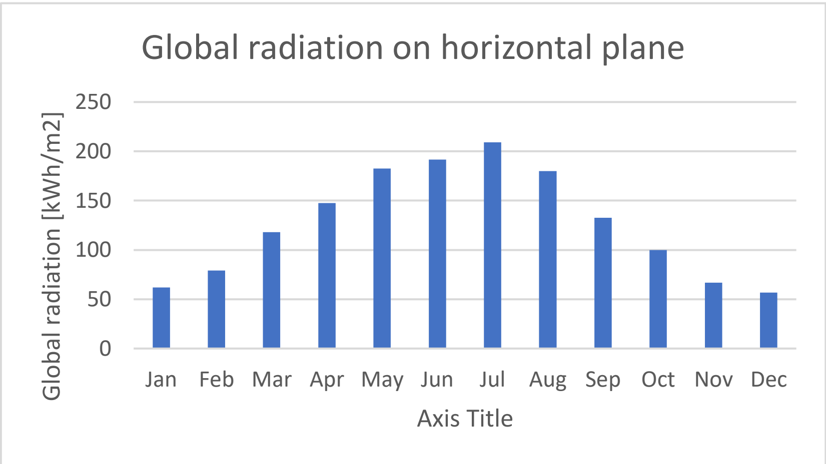


Figure 5.1 - Global radiation on horizontal plane. The source is the database of the software PSOL utilized to simulate the photovoltaic system.

The year total value amount to 1526 kWh/m2 and the average monthly to 127 kWh/m2. This Spanish radiation is one of the strongest in Europe and this enforce the choose done in this study.

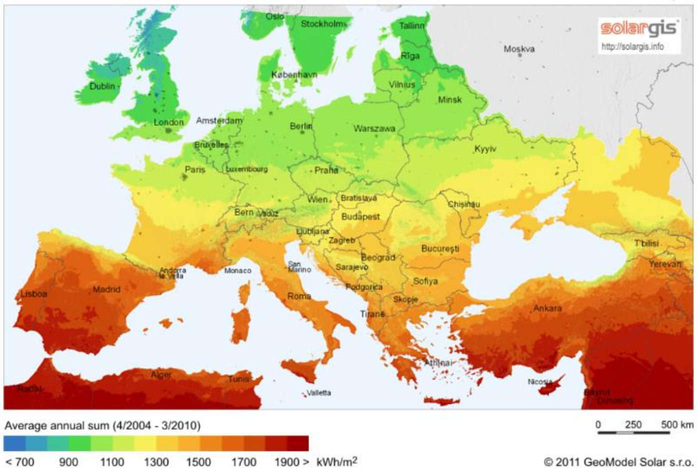


Figure 5.2 - Average annual radiation in Europe **[30]**

5.1.2. Legislation

Currently, the Spain has developed a regulation to increase the renewable energy production, creating a framework that encourage the consumers to generate their own energy by local production. This imply the diminution of pollution that is generating every time power plant burn fossil fuels and the creation of an electricity network self-sufficient that guarantee the availability of electricity in any case without importing from other states. Moreover, the structure of the grid is reinforced with a non-centralized production reducing the cable losses.

It is for this reason that this new regulation is aimed at the development of Law 54/1997 and of European Community 2007/8/CE and 2009/28/EC directives focused on the development of renewable and sustainable energies.

This system made feasible to realize power generation installations not superior to 100kW$_{el}$ nominal using photovoltaic, thermoelectric, geothermal, wave, tidal, ocean thermic and wind technologies. Furthermore, there is the possibility of carrying out these installations both in urban and rural areas, making a maximum of one installation for cadastral reference.

Also, an economic saving is expected for the promoter, in terms of the requirements at the point of connection with the grid. In fact, after these directives there is no more need to pay for connection point studies neither for carry out modifications in the electrical infrastructure of the company at the point of connection with the national grid.

5.1.3. Basis of photovoltaics systems

The principle of operation of grid connection photovoltaic systems is the transformation of solar radiation into electric energy. To carry out this transformation, photovoltaic systems require 2 indispensable components: The photovoltaic field and the power inverter.

The function of the photovoltaic field, roughly speaking, is to capture the solar radiation, and transform it into energy in the form of direct current (DC). It is composed by various modules which in turn are formed by a set of crystalline silicon photovoltaic cells that generate a potential difference and a current proportional to the solar radiation received.

To be able to use this electric energy, in a grid connected system, adaptations must be done to the technical conditions of the electrical distribution network, that works in alternating current (AC) at a voltage of 230/400 V and a frequency of 50 Hz. To carry out these adaptations, the power inverter is employed. It can provide a voltage and a current stabilized to the standards, starting from the energy supplied by the photovoltaic field. In addition, it is also capable of providing the safety standards required by an AC generator device connected to the distribution network, for instance, the plant must be disconnected from the grid when it fails or when oscillations of voltages, currents and electrical signal frequency occur. The inverter usually performs also MPPT (maximum power point tracking) i.e. optimizes the operation of the system keeping the current (I) and the voltage (V) around the values that give the maximum power obtainable for a certain solar radiation and external temperature.

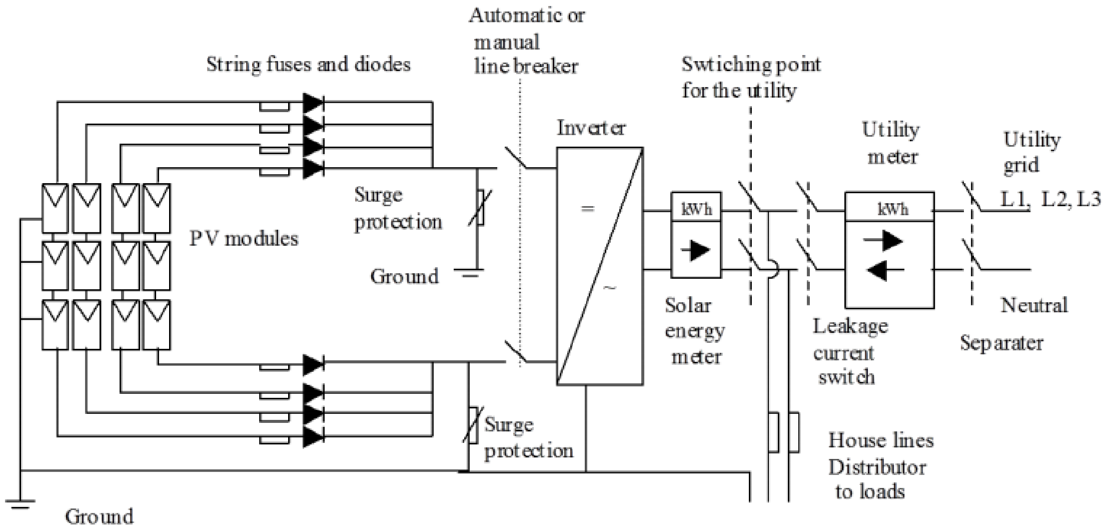


Figure 5.3 - Generic photovoltaic grid-cnnected scheme

5.1.4. Configuration of the photovoltaic array

To configure the photovoltaic field the software PVSOL is employed. It optimizes the size of the system for a certain power peak decided, that is 100 kW_{el} as the law allows. So, the brand selected for the panels was the Yingli Green Energy due to the availability given by the providers of the zone. They suggest a YL310P-35b module able to supply 310 Wp. It is a multi-crystalline silicon solar cell with 72 cells. The module dimension is 1,97mx0,99m. Its technical specifications are listed in Tab.5.1, they are valid for standard test conditions (STC) i.e. for a solar irradiance of 1000 W/m^2, 25°C module temperature and AM1.5g spectrum according to EN 60904-3.

Conditions	STC
Tamb [°C]	25
Isc [A]	8,99
Voc [V]	45,6
Impp [A]	8,53
Vmpp [V]	36,3
Pmax [W]	310
FF [-]	75,53%
module efficiency	15,90%
module area [m^2]	1,970x0x990

Table 5.1 - Yingli YL310P-35b operating characteristics for STC

Nominal operating cell temperature [°C]	46 +- 2
Temperature coefficient of Pmax [%/°C]	-0,45
Temperature coefficient of Voc [%/°C]	-0,33
Temperature coefficient of Isc [%/°C]	0,06
Temperature coefficient of Vmpp [%/°C]	-0,45

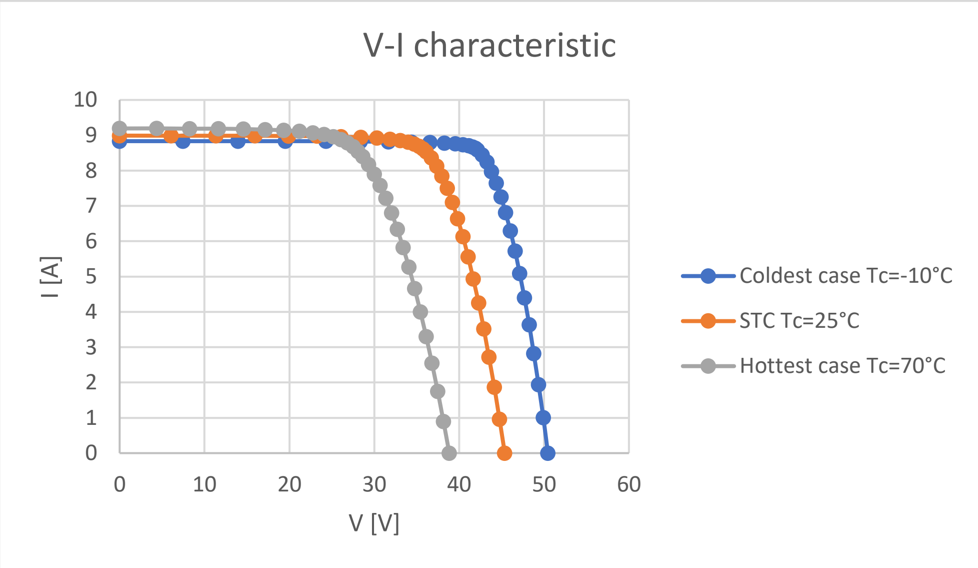
Table 5.2 - Yingli YL310P-35b thermal characteristics

The inverter chosen instead, also due to the availability from the same provider of the photovoltaic panels, is a Fronius Agilo 100.0-3. As the name suggest the maximum power that it can convert is of 100 kVA equal to the one desired for the photovoltaic field. Its characteristics are listed in Tab.5.3:

max. input current [A]	227
max. input voltage [V]	950
max. array sc current [A]	340,5
min. mpp voltage [V]	460
max. mpp voltage [V]	820
maximum efficiency	97,2%

Table 5.3 - Fronius Agilo 100.0-3 technical characteristics

Before entering in the design phase, it is worth to shows how the technical specifications of the photovoltaic module vary with its temperature (coefficient reported in Tab.5.2). This is needed to do a better dimensioning between the photovoltaic field and the inverter, avoiding mismatch during the year. Hence the software PSOL use the two cell temperatures Tc=-10°C and Tc=70°C that correspond to the extreme cases, as to say the coldest case (for the winter) and the hottest case (for the summer), as typically used for a Mediterranean climate like in Barcelona. The V-I and the V-P characteristic curves can be seen in the following Fig.5.4:



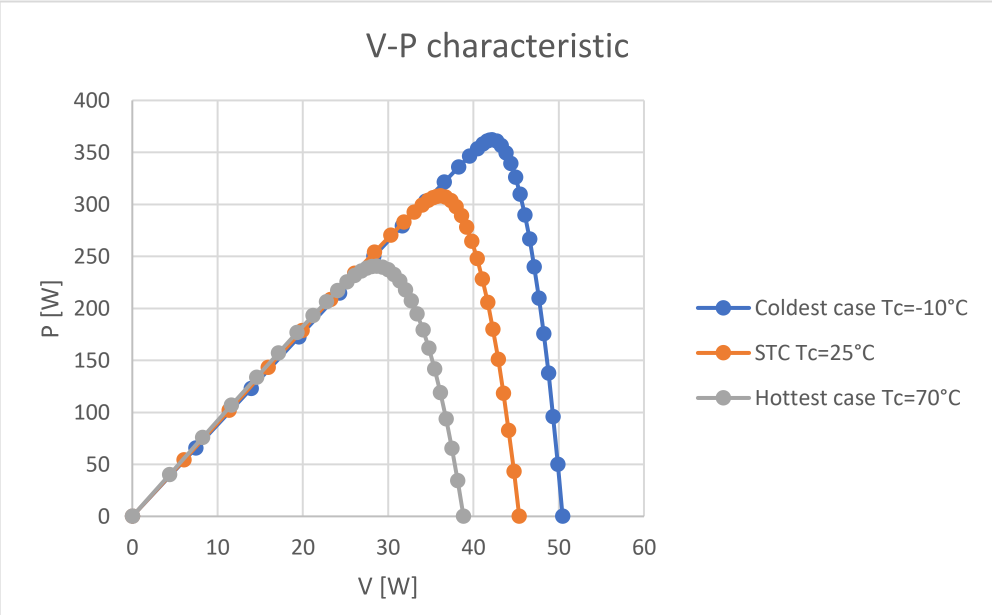


Figure 5.4 - Module electric characteristics parametrized for the three temperatures

For these two curves the values needed for the dimensioning are extrapolated and reported in the following Tab.5.4:

Tc [°C]	-10	70
Isc [A]	8,83	9,19
Voc [V]	50,45	38,84
Impp [A]	8,59	8,4
Vmpp [V]	42,17	28,65
Pmpp [W]	362,08	240,51

Table 5.4 - Operating characteristics at different temperatures

To design the solar field the first step is calculating how many panels are needed for an installation with a peak power ≥100 kWp. This is done simply dividing the target power by the module maximum power output as following:

$$N°tot = \frac{P}{P_{max}} = \frac{100.000\ W}{310\ W} = 322{,}58 \rightarrow\ 323$$

The number obtained is not integer, so it is rounded to the excess. But due to this, the actual peak power of the installation will be slightly higher, it can be recalculated multiplying the number of modules selected by their maximum power output:

$$P_{peak} = N°tot\ P_{max} = 323 \cdot 310\ W = 101{,}13\ kWp$$

Now to decide how many panels are going to be connected in series it is needed to look both at the specification of the inverter and the panels. The inverter allows a maximum power input of 950 V as written in tab.5.3. So, the maximum number of modules that can be connected in series must be lower or equal than:

$$N°\ series\ max = \frac{V_{dc,max}}{V_{oc}(-10°C)} = \frac{950\ V}{50{,}45\ V} = 18{,}83 \rightarrow 18$$

Moreover, in the maximum power point conditions (mpp) the inverter has a voltage range of 460 to 820 V. From these values other two conditions are derived:

$$N°\ serie \geq N°\ series\ min = \frac{V_{mpp,min}}{V_{oc}(70°C)} = \frac{460\ V}{28{,}65\ V} = 16{,}06 \rightarrow 16$$

$$N°\ series \leq N°\ series\ max = \frac{V_{mpp,max}}{V_{mpp}(-10°C)} = \frac{820\ V}{42{,}17\ V} = 19{,}45 \rightarrow 19$$

The last condition is relative to the maximum number of panels that can be connected in parallel and to do this the maximum input current is used as following:

$$N° \, parallel \leq N° \, parallel \, max = \frac{I_{mpp,max}}{I_{mpp}(-10°C)} = \frac{227 \, A}{8{,}59 \, A} = 26{,}44 \rightarrow 26$$

Given all the conditions to be respected the possibilities are the following:

1. $N° \, series = 16 \quad N° \, parallel = \frac{N° \, tot}{N° \, series} = \frac{323}{16} = 20{,}18 \rightarrow 21$
2. $N° \, series = 17 \quad N° \, parallel = \frac{N° \, tot}{N° \, series} = \frac{323}{17} = 19$
3. $N° \, series = 18 \quad N° \, parallel = \frac{N° \, tot}{N° \, series} = \frac{323}{18} = 17{,}94 \rightarrow 18$

The third possibility is chosen because it comports the utilization of 323 exact modules, as defined before, while the other two imply a higher number of total modules, choice that would result in a higher cost and a higher peak power than the maximum allowed one. (the final scheme is represented in the Ann.14)

The total area of the panel is the area of one module multiplied for the total number of modules:

$$A_{field} = 323 \cdot 1{,}97 \, m \cdot 0{,}990 \, m \simeq 630 \, m^2$$

5.1.5. Physical installation

The arrays as configured in the previous paragraph will be installed on the roof of the building. To calculate the area that they will occupy it is firstly needed to configure their relative position with the sun and between them. To do this the reader should refer to Fig.5.5.

The roof mentioned is completely flat, as consequence its angle can be taken as null (β_1=0) and so the angle β correspond to the inclination of the panel with respect to the horizontal surface. It is the result of the optimization through the year. In fact, for each month there is an optimal inclination angle, but being absent a sun tracking system, with a fixed inclination it is needed to find an average value that is taken as 35° for the factory latitude and the generating surface of the devices will be facing the South. From the inclination angle it is possible to calculate the height h that the support structure will permit that is:

$$h = b \sin \beta = 0{,}99 \, m \cdot \sin 35° = 0{,}57 \, m$$

Instead the base occupation that in the Fig.5.5. is d-d_1 is:

$$d - d_1 = b \cos \beta = 0{,}99 \, m \cdot \cos 35° = 0{,}81 \, m$$

Now it is needed to calculate the distance between the panels d_1 and it is done considering the shadow that they can project to the adjacent ones. It is common to choose d_1 to ensure at least 4 hours of sun around midday on the winter solstice. In any case IDEA suggest the following formula [7]:

$$d1 = \frac{h}{\tan(61° - latitud)} = \frac{0{,}57}{\tan(61° - 41{,}65°)} = 1{,}6\ m$$

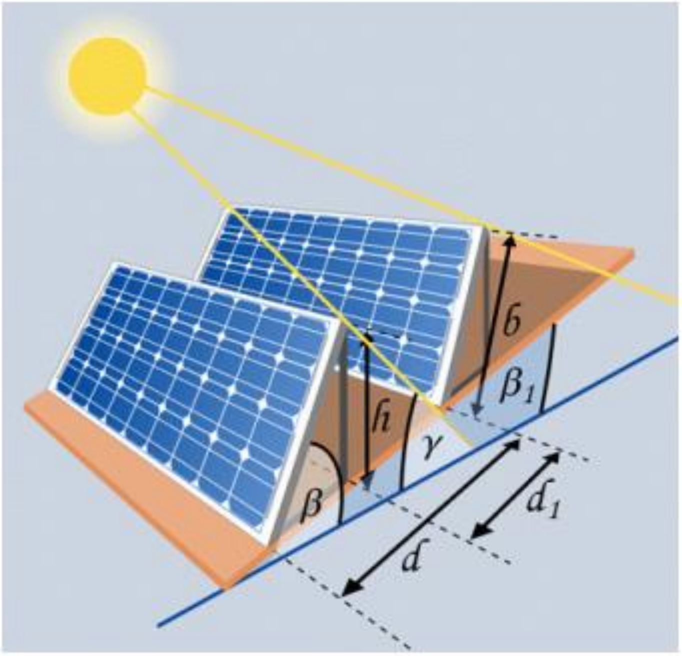


Figure 5.5 - Angles convention for configuring the modules position with respect to the sun and to the plane

In the Fig.5.5 is not present the azimuth angle α, that is the angle between the projection on the horizontal plane of the normal to the surface of the module and the meridian of the zone. It is taken as 0°C to orient the surface of the panels always at south toward the sun.

Given those dimensions the total area that the solar field will occupy is calculated as follow:

$$A = N°\ tot \cdot d \cdot 1{,}97\ m = 323 \cdot 2{,}43\ m \cdot 1{,}97\ m \simeq 1.550\ m^2$$

For a total weight of 8.660 kg.

The area to occupy is lower than the available one of the roof, so the system plant is the one in Fig.5.6 where the purple areas are some flat obstacles, but principally composed by windows that bring the sunlight during the day and have to remain clear. No big obstacles are present in the roof neither around it, thanks to its height. Hence no shadow is considered in the calculation of the software.

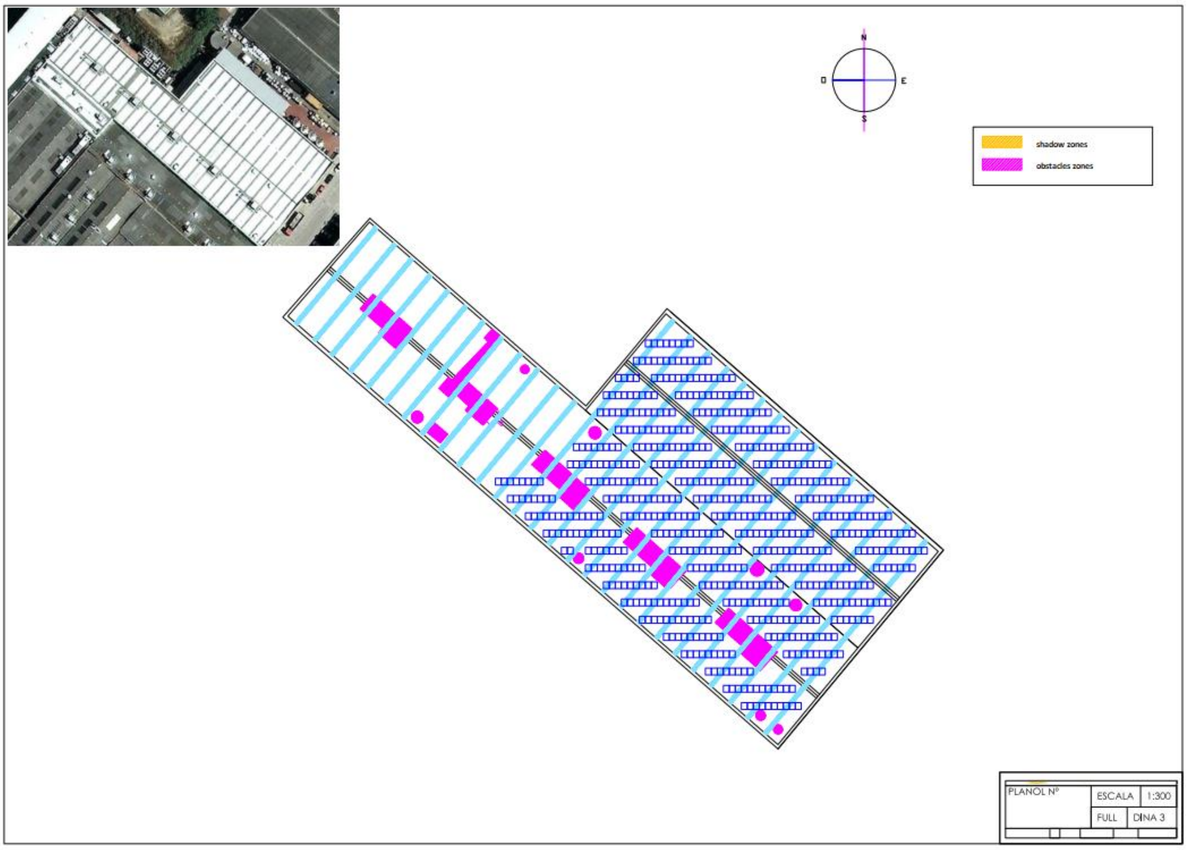


Figure 5.6 - Roof plan, real satellite photo and scheme of the photovoltaic field.

A complete system of aluminium structure can be supplied by the provider to mount the photovoltaic modules in horizontal. The system is composed by the substructure profiles, the triangles that provide the necessary inclination and the profiles for fixing the modules on the triangles. In addition to this all small auxiliary material for proper operation and safety of it will be considered.

Moreover, the installation comprises the electrical system to protect the installation and measure the operating parameters. It consists of a protection box at the exit of the inverters, with magneto thermal and differential protection, and a measurement box that incorporates a general protection of the entire installation with sectioning, and an approved company counter. This item also incorporates all the necessary electrical equipment for the connection of the inverter modules and protection and measurement boxes.

5.1.6. Energy generation

Once inserted the main inputs like the ones calculated in the previous section, the software performs an hourly simulation of one year. To calculate the energy generation the first step is calculating the average radiation on the generation plane from the radiation on the horizontal plane considering the shadow losses, that are null in this case, the azimuth, that is 0° i.e. south and the inclination of the modules, that is 35°. This can be done utilizing the following formula [7]:

$$G(\alpha,\beta) = G(0°)\,\{1 + 100\,[1{,}2 \times 10^{-4}\,(\beta - 41° + 10)^2 + 3{,}5 \times 10^{-5}\,\alpha^2\}$$

To this energy the following losses/gain as to be removed/added to find the global radiation at the module, that is the net energy that from the sun impact directly the generating surface of the photovoltaic panels:

- **Deviation from standard spectrum:** Spectral mismatch changes the module's characteristic curve, which is measured against a standard spectrum. It is taken as -1% for the total irradiation of the year.
- **Ground reflection (Albedo)**: PV array irradiation is increased by the reflection of radiation on the ground or in the surrounding area. With a ground covering of snow the albedo is 80%, under normal conditions the albedo is 20%. The annual gain due to this effect is of +1,79%
- **Reflection on module interface:** module characteristics are determined at STC which assume perpendicular incident solar rays. In real conditions larger incident angle occur, implying higher reflection losses than the nominal one. They amount to -2,01% for the whole irradiation of the year.

From this, subtracting the losses due to soiling (i.e. due to the accumulation of dirt on the solar panels, they are assumed to be 2% for all the year) and utilizing the module area and efficiency of Tab.5.1, the rated photovoltaic energy is calculated.

This energy calculated is still rough solar energy in the form of radiation, to find the AC electricity that can be used the losses due to its transformation must be considered, they are [8]:

- **Losses due to Low-light performance:** taken as -1,2% they consider the efficiency deviation from the nominal one due to solar radiation lower than 1000 W/m2.
- **Losses due to Deviation from the nominal module temperature:** as explained before, depending on the ambient and so on the cell temperature the operating conditions changes and so does the efficiency. Taken as -2,8 %
- **Diodes:** losses caused by a drop-in voltage by the modules blocking diodes (-0.5%)
- **Losses due to MPP Matching:** due to mismatch between the amounts of energy generated by two or more modules of the arrays because the output of the entire PV module under worst case conditions is determined by the solar cell with the lowest output. They can be caused principally by the partial shading of the generating surface, and as the shadow is assumed null they are very low, i.e. -0,1% for the study
- **Losses due to Mismatch (Manufacturer Information):** due to the same reasons of the previous losses, but as consequence of the module unicity. Taken of -1,9%
- Input voltage deviates from rated voltage: taken as -0,4%
- **DC/AC Conversion:** they are due to the inverter efficiency of Tab.5.3
- **Cable losses:** they represent the dissipation of the cables due to ohm effect. Taken as -0,8% of the total energy generated

So, the final monthly energy balance is reported in the following Tab.5.5:

	G(0°)	G(α,β)	∑ losses 1	Global Radiation at the Module	Rated photovoltaic energy	∑ losses 2	PV energy (AC)
Month	kWh/m²	kWh/m²	kWh/m²	kWh/m²	kWh	kWh	kWh
Jan	61,99	107,03	-1,09	105,94	10.383	-699	9.684
Feb	79,26	115,05	-1,1	113,96	11.169	-772	10.397
Mar	117,97	142,35	-1,33	141,02	13.822	-1.162	12.660
Apr	147,4	156,8	-1,65	155,15	15.206	-1.428	13.778
May	182,5	173,17	-2,02	171,15	16.775	-1.722	15.053
Jun	191,65	173,39	-2,11	171,28	16.788	-1.892	14.896
Jul	209,25	193,46	-2,21	191,25	18.745	-2.489	16.256
Aug	179,86	180,9	-2,04	178,87	17.532	-2.361	15.171
Sep	132,47	149,66	-1,52	148,14	14.519	-1.778	12.741
Oct	99,89	135,68	-1,23	134,45	13.178	-1.402	11.776
Nov	66,66	101,9	-1,04	100,86	9.886	-799	9.087
Dec	56,8	106,34	-1,2	105,14	10.305	-681	9.624
year	1525,7	1735,72	-18,53	1717,19	168.310	-17.190	151.120

Table 5.5 - Energy balance with the two group of losses

This section can be concluded saying that being the electric load of the chiller always higher than the photovoltaic electricity generation all the energy generated is instantaneously consumed without withdrawal with the national grid.

5.1.7. Cost of installation

For this first technology the cost is taken from a real offer done by a provider contacted. It amounts of 123.000,00 € of initial investment that doesn't include the annual cost for maintaining the system. All other expenses, such as transport costs, availability of other means and possible collection and return of equipment for repair in the manufacturer's workshops are included. Also, labor and materials necessary to install the technology and eventual adjustments to the operation of the installation are included.

For the maintenance program that must guarantee all the operation necessary for keeping the installation in the acceptable conditions during all the useful life (estimated to be around 20 years) it is calculated a cost 1,30% of the investment one. It is divided in preventive and corrective. The preventive maintenance plan includes: visual inspection operations and verification of parameters to maintain within acceptable limits the operating conditions, the performance and the protection. The corrective maintenance plan instead includes all replacement operations necessary to ensure that the system functions correctly during its useful life.

For the annual cost it is also considered the electricity consumption of the electric devices estimated to be around 0,13% of the investment cost.

5.2. Absorption chiller

5.2.1. Physical principles

Until this point the absorption chiller was always considered as a black box, i.e. a machine that intake a hot water flow rate to generate a chilled water flow rate. In this section finally, its basis will be presented and some consideration about its operating conditions will be discussed.

The second law of thermodynamics in the Clausius form, establish the impossibility of having as the sole result of one or more thermodynamic transformations, the passage of a certain quantity of heat from a source at a certain temperature T1 to another at a higher temperature (T2>T1). To obtain such a transformation, a "compensating effect" is required. In compression refrigerant cycles this effect is represented by the transfer of a certain amount of work L, to the working fluid. Instead, in absorption refrigeration cycles, the compensating effect is the passage of a certain quantity of heat Q' from a source at temperature T4 to another at a lower temperature (T3<T4) Fig.5.7 [8].

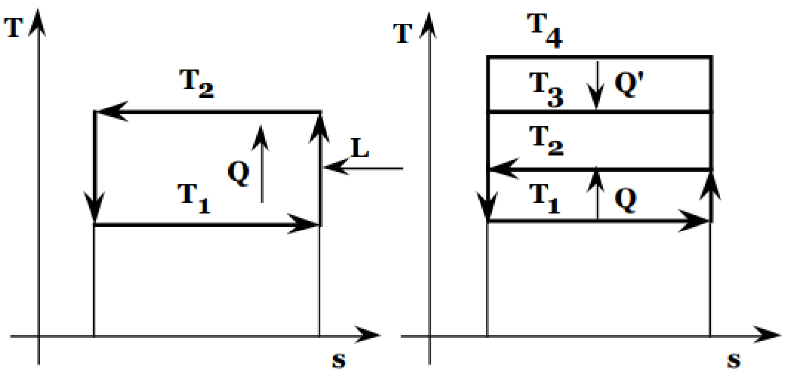


Figure 5.7 - On the left is represented an ideal refrigeration compressor cycle and, on the right, an ideal refrigeration absorption cycle

The operating fluids of the absorption refrigeration systems are binary solutions of refrigerating fluid with variable concentration in a solvent. The system studied in the project for example, employ water as refrigerating fluid and Lithium Bromide (LiBr) as solvent.

Before the explanation of the operating principle of the scheme in Fig.5.8 [8] it is useful to introduce the flow rates and their concentration of solvent:

1. Gv no solvent present, is a pure flow of refrigerating fluid
2. Gp high concentration of solvent (concentrated solution)
3. Gr=Gv+Gp low concentration of solvent (diluted solution)

The cycle starts in the generator G, where the low concentration flow Gr boils, thanks to the provision of a thermal power Qg (in the case study it comes from the compressor heat recovery), and the flow of pure refrigerant fluid Gv evaporates and separates from the high concentration flow Gp. Then the pure refrigerating fluid flow Gv condense in the condenser C yielding the thermal power Qc. So, it is laminated in the valve V from the pression pc to the pression pv and evaporated in the evaporator E, receiving the thermal power Qe that is the useful effect of the refrigeration cycle.

The vapor flow of pure refrigerating fluid Gv, leaving the evaporator E, is drowned in the liquid solution Gp with a high concentration of solvent obtained before in the section G, in the absorber A with release of the thermal power Qa. The diluted solution (Gr = Gp + Gv), low concentrated in solvent, is compressed up to the condensation pressure pc, (with negligible mechanical power expenditure P compared to the similar compression of steam of the vapor-compression refrigeration systems) and sent in the section G to start again the cycle. The exchanger S allows the recovery of thermal power between the hot flow Gp, which exit the generator to enter the absorber, and the cold flow Gr, which leave the absorber to enter the generator.

The cycle section: absorber-pump-heat exchanger-generator highlighted in Fig.5.8 receives the steam flow Gv, of low pressure refrigerant fluid (physical state 1), and provides the same saturated steam flow as refrigerating fluid at the condensing pressure (physical state 3), thus replacing the compressors group of vapor-compression refrigeration systems, whose mechanical compression power (neglecting the pump power) is replaced, as refrigeration compensating effect, from the thermal power Qg spent in the generator.

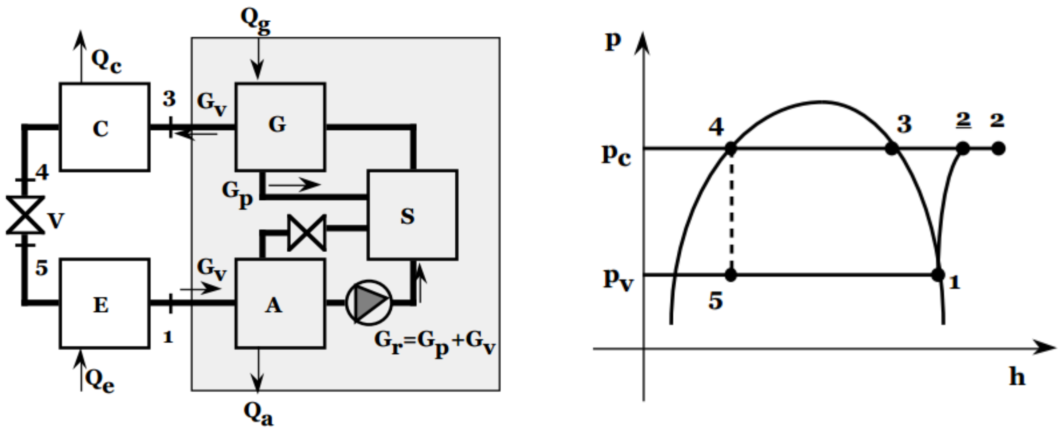


Figure 5.8 - On the left it is represented the basic scheme of an absorption refrigeration cycle and on the right the pressure vs enthalpy chart

The useful effect of this cycle is the refrigeration effect Qe and the expense is the heat provided to the cycle Qg, so to evaluate the performances the COP is defined as:

$$COP = \frac{Qe}{Qg}$$

The energy balance is the following:

$$\mathrm{Qo} = \mathrm{Qa} + \mathrm{Qc} = \mathrm{Qe} + \mathrm{Qg} + \mathrm{P} \cong \mathrm{Qe} + \mathrm{Qg} \qquad \mathrm{Eq.}\ (2)$$

With the assumption of ideal transformation, the total entropy variation is null and so the following is valid:

$$\Delta S = \sum \frac{Q}{T} = -\frac{Qg}{Tg} - \frac{Qe}{Te} + \frac{Qo}{To} = 0$$

Where Tg is the temperature in the generator, Te is the evaporation temperature and To is the ambient temperature. Then, for the Eq.(2):

$$\frac{Qg}{Tg} + \frac{Qe}{Te} = \frac{Qg}{To} + \frac{Qe}{To}$$

Thus, the COP can be defined, for an ideal cycle as:

$$COP = \frac{Tg - To}{To} \frac{Te}{To - Te} \qquad Eq.(3)$$

Thus, appears that (Tg - To)/Tg can be considered as the efficiency of the ideal motor cycle operating between the extreme temperatures Tg and Te, and Te/(To-Te) the coefficient of the refrigerating effect of the ideal compression cycle operating between the temperatures To and Te. In the case of ideal transformations starting from a primary thermal energy, the same refrigerating effect can be obtained either by directly using it in an absorption refrigeration cycle or by passing through its transformation into mechanical energy to be used in a compression refrigeration cycle.

On the other hand, for real transformations, the performance ratio is clearly in favor of compression cycles (Qe/Qg≃1), compared to absorption cycles (Qe/Qg≃0.5) if the primary thermal energy derives from fuels and/or is available at sufficiently high temperatures for its efficient conversion into mechanical power. Instead, since the temperature levels required for the thermal power that feed the absorption devices are definitely more modest (100 ÷ 200°C), the absorption cycles can be advantageous if the primary thermal energy is available at temperatures for which the work conversion efficiency is reduced to uneconomical levels, i.e. if the thermal energy derives as a by-product of other processes and must be dissipated outside. And this is exactly the case of the factory in study, where the air compressors are dissipating a relevant amount of thermal power at relatively low temperature (100°C).

5.2.2. Sizing and study of the device employed

The characteristics of the absorption chiller proposed in this study are given by Systema, a company of the sector that was contacted for the furniture of the device. They give the possibility of customizing the chiller for the case needed.

The first step is determining the size of the absorption chiller needed and this is done looking at the maximum thermal power available from the compressor, that is founded multiplying the maximum electric consumption by the percentage of recoverable heat founded in the paragraph 4.3.2:

$$Q_{max} = 175\ kW_{el} \cdot 28\% = 49\ kW_{th}$$

So, to find the maximum refrigeration power (i.e. the power absorbed by the evaporator Qe) that can be generated by the absorption group it is needed to multiply this thermal power (i.e. the power supplied to the generator Qg), by the COP, suggested as 0,70 by Systema:

$$Q_e = Q_{max}\ COP = 49\ kW_{th} \cdot 0{,}70 = 34\ kW$$

The machine suggested that at the best fit these operating conditions is a hot water driven single effect water lithium bromide absorption chiller model SYDHL-35, adapted to have a major temperature difference at the generator. Its characteristics are reported in the following Tab.5.6:

Refrigerated water	flow rate [m3/h]	6
	T in/out [°C]	7/12
	Qe [kW]	35
Hot water	flow rate [m3/h]	2.9
	T in/out [°C]	80/95
	Qg [kW]	50
Cooling water	flow rate [m3/h]	15
	T in/out [°C]	30/36
	Qc [kW]	30

Table 5.6 - SYDHL-35 operating conditions

Its scheme is the one of Fig.5.9, and it is composed by [9]:

- **Generator:** After exiting the heat exchanger, the dilute solution moves into the upper shell. The solution surrounds a bundle of tubes which carries the hot water that transfers heat into the pool of dilute lithium bromide solution. The solution boils, sending refrigerant vapor upward into the condenser and leaving behind concentrated lithium bromide. The concentrated lithium bromide solution moves down to the heat exchanger, where it is cooled by the weak solution being pumped up to the generator.
- **Condenser:** The refrigerant vapor condenses on the tubes bundles of the condenser. The heat is removed by the cooling water which moves through the inside of the tubes. As the refrigerant condenses, it is collected at the bottom of the condenser.
- **Evaporator:** The refrigerant liquid moves from the condenser in the upper shell down to the evaporator in the lower shell and is sprayed over the evaporator tube bundle. Due to the extreme vacuum of the lower shell (≃0.8 kPa absolute pressure), the refrigerant liquid boils at approximately, creating the refrigerant effect. (This vacuum is created by hygroscopic action in the absorber)

- **Absorber:** As the refrigerant vapor migrates to the absorber from the evaporator, the concentrated LiBr solution from the generator is sprayed over the top of the absorber tube bundle. This concentrated solution actually pulls the refrigerant vapor into solution, creating the extreme vacuum in the evaporator. The absorption of the refrigerant vapor into the lithium bromide solution also generates heat which is removed by the cooling water. The now dilute lithium bromide solution collects in the bottom of the lower shell, where it flows down to the solution pump to go again in the generator.
- **Solution heat exchanger:** It recycles the heat of the concentrated solution in the generator, improving the thermodynamic efficiency of the system.
- **Auto-spurge system & vacuum pump:** The two devices combine to form an air pumping system that expels the non-condensable gases of the system, ensures performance and maximizes system life. The incondensable gases are collected in a tank of generous dimensions that allow to enlarge the time of the bleeding itself, carried out through the vacuum pump integrated with the absorber
- **Refrigerant pump:** It is used to provide and spray uniformly cooling water on the evaporator tube heat exchanger.
- **Diluted solution pump:** It collects the LiBr solution from the bottom of the absorber shell to distribute it in the system.
- **Concentrated solution pump:** It is needed to send the concentrated solution from the bottom of the generator to the solution heat exchanger and then to the absorber.
- **Regulation valve:** 2 or 3-way motorized valve able to regulate the flow of the hot water supply so that there is the automatic modulation of the cooling capacity.
- **Anti-crystallization system:** A system for detecting temperatures and deviations from the standard operating conditions. It allows the chiller to monitor an excessive concentration of the solution. In the event of anomalies, the chiller will automatically flow the refrigerant water to the concentrated solution to dilute the solution maintaining the concentration well below the critical crystallization point. In the event of a sudden power failure or abnormal system shutdown, the system will quickly start to dilute the LiBr solution and ensure rapid dilution.
- **Control system:** The control system includes a series of electronic switches, for example the programmable control unit, the touch screen, the transducer, the temperature acquisition module, the analogue output module, the liquid level regulator, the AC contactor, the thermal relay and the intermediate relay. It is equipped with peripheral input sensors that include the destination switch, the flow meter, the electrode-type level switch, the resistance thermometer and the pressure switch. An important feature is the automatic load adjustment that when there is a change in the load, for example a change in the heat input, monitor and regulate the chiller parameters like the solution flux to guarantee the optimized efficiency.

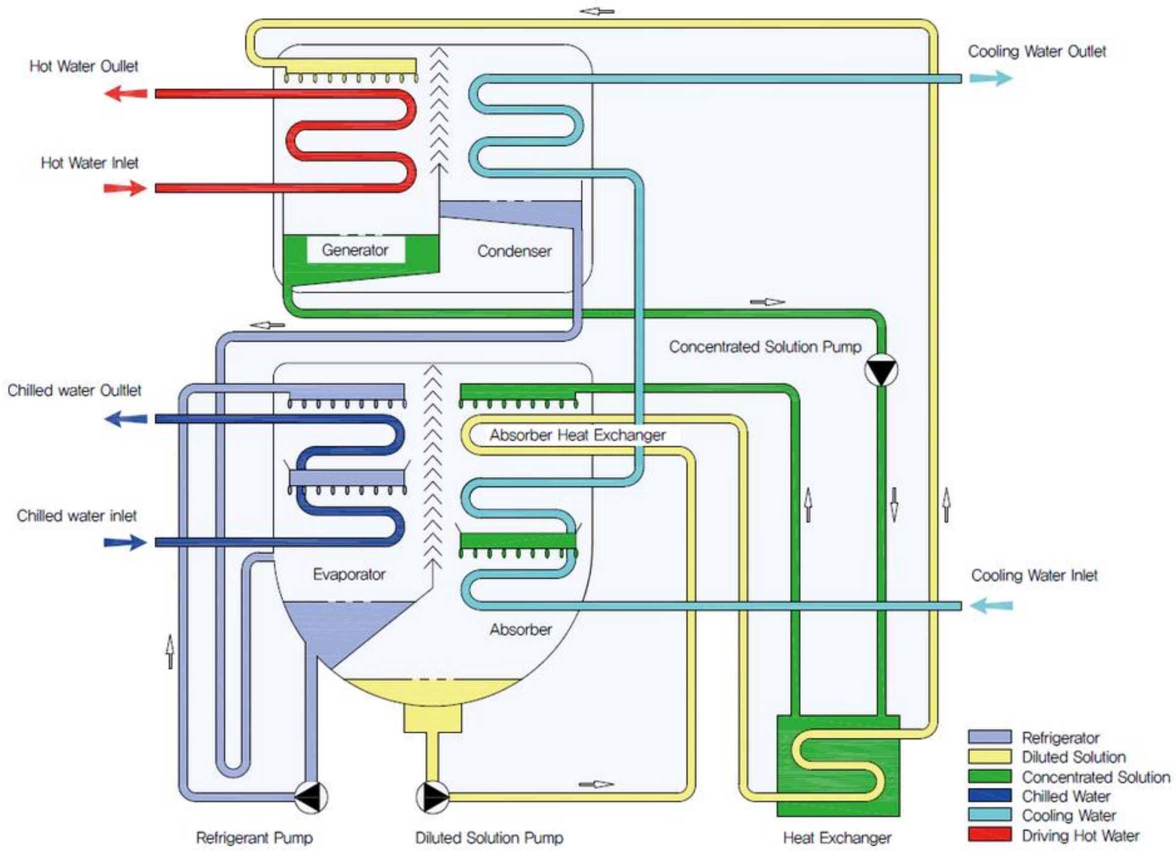


Figure 5.9 - Single effect hot water driven absorption chiller scheme [18]

For its operation some assumptions are done. The first is that the electrical consumption of the pumps, that is 0,3 kW_{el}, is neglected as in the energy balance of Eq.(2). So, the refrigeration capacity that it will supply is:

$$Q_{refr} = Q_e = Q_g \; COP(Tc)$$

The Q_g in the formula corresponds to the heat recuperated by the compressor, that vary in function of its load, while the COP is function only of the condenser temperature Tc as it will be explained in the next rows.

As mentioned in the compressor section, the thermal power Q_e is available at a fixed temperature of 95°C, so looking at Eq.(3) it is deduced that the COP is not function of the generator temperature, because it is constant. Moreover, also the chilled water is generated at fixed temperature. Instead, the performance coefficient is affected by the temperature of the cooling water going inside the machine. In fact, it increases with decreasing the condensing temperature, that is controlled by the cooling water refrigerated by the evaporative tower. This happen because both the absorber and the condenser work better for low temperatures: in the absorber the absorption of water by the Lithium Bromide is a chemical reaction that present higher efficiency if cooled, and in the condenser the water vapor need to condensate releasing an amount of heat [10]. It is remembered that the absorber and the condenser are refrigerated with the same cooling water that will be generated with a cooling tower connected as in Ann.13.

Therefore, considering the temperatures of the hot water and of the refrigerated water at the reference values of Tab.5.6 (respectively 95°C and T 12°C), the COP will depend on the temperature of the cooling water entering the absorber by the following correlation [10]:

$$COP = -0{,}0007\,T_{cw,in}^2 + 0{,}023\,T_{cw,in} + 0{,}6449$$

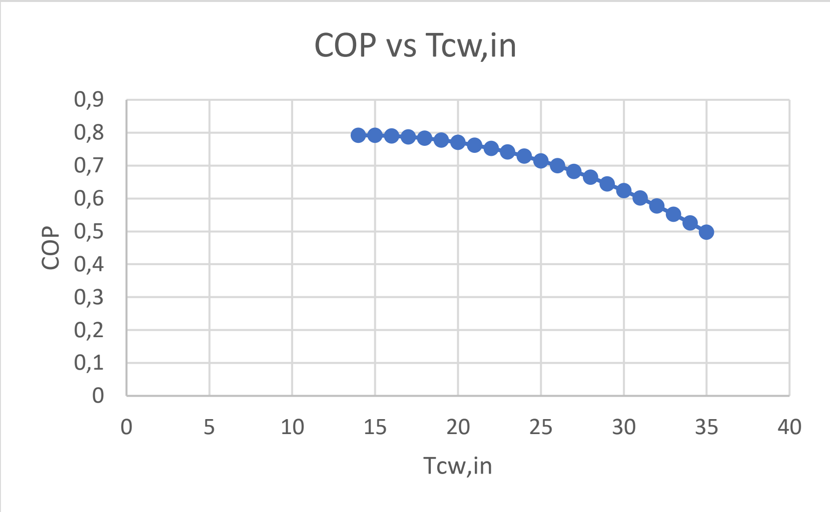


Figure 5.10 - Behaviour of the absorption chiller COP in function of the environment temperature

To find the cooling water temperature entering the absorber it is needed to look at the cooling tower. Its scheme is depicted in Fig.5.11. It uses evaporative cooling to reduce the temperature of the water flux. Their efficiency can be expressed as [12]:

$$\mu = \frac{T_{cw,out} - T_{cw,in}}{T_{cw,out} - T_{wb}} \quad where\ in/out\ are\ referred\ to\ the\ absorption\ chiller$$

They can achieve water temperatures below the dry bulb temperature of the cooling air (that correspond with the ambient temperature T_{amb}), but the maximum efficiency is limited by the wet bulb temperature of the cooling air (T_{wb}). The efficiency is founded for the nominal conditions and kept constant varying the wet bulb temperature of the environment to find the new $T_{cw,in}$

$$\mu = \frac{36°C - 30°C}{36°C - 25{,}4°C} \backsimeq 57\%$$

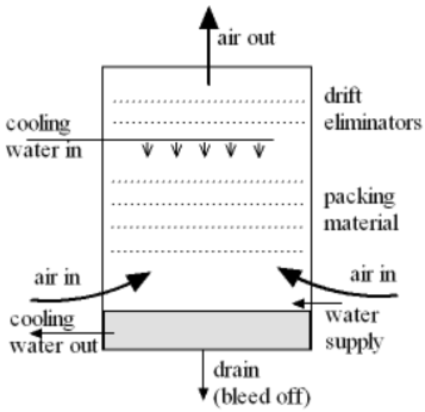


Figure 5.11 - Cooling tower operation scheme. Attention to not confuse the in/out index with the in/out of the absorption chiller

The nominal T_{wb} comes from the technical specification given by the company, and it is chosen for the worst case of the month, i.e. when the ambient wet bulb temperature is at a value that permit the cooling tower to generate water at a temperature of 30°C. This is done to avoid drastic worsening of the COP of the absorption chiller.

To find the wet bulb temperature it should be employed the humid air diagram of Ann.12, but due to the need of calculating it for each hour of the year, the following correlation [14] is used, assuming a relative humidity RH of 74% [13] constant through the year:

$$T_{wb} = T_{amb}\,\mathrm{atan}[0{,}151977(RH\% + 8{,}313659)^{\frac{1}{2}} + \mathrm{atan}(T_{amb} + RH\%) - \mathrm{atan}(RH\% - 1{,}676331) + 0{,}00391838(RH\%)^{\frac{3}{2}}\,\mathrm{atan}(0{,}023101\,RH\%) - 4{,}686035$$

The water consumption, or the amount of make-up water, of a cooling tower is about 0,057 l/min/kW_{th} of refrigeration. So, for the case in study there will be a consumption of (the refrigeration needed is the Qc of Tab.5.6):

$$m_{water} = 0.057 \cdot 29{,}7\,kW = 1{,}69\frac{l}{min} = 0{,}10\frac{m^3}{h}$$

5.2.3. Cost of installation

As for the solar panels the cost derives from the offer of the provider, that gave a cost of 343,00 €/kW_{th}. So, the cost for a machine of 35 kW_{th} amount to 12.005,00 €. The price includes the cooling tower. Its useful life is estimated to be 10 years, so, due to the 20 years studied in this work it has been decided to buy a new one after 10 years.

The provider gives a contract for an annual maintenance cost of the 2% of the investment cost. But to calculate the total annual cost it is needed to add also the make-up water that cost 0.8 €/m3 for this industry, yielding a total cost of 700,00 €/year.

5.3. Stratified chilled water storage tank

5.3.1. Cool thermal storage for peak-shifting

This technology is usually employed in the air conditioning field for shifting the refrigeration load from the peak hours to the off-peak ones that have cheaper costs of electricity. This strategy is adopted either for the savings that the difference of costs would imply, or for demand limiting, i.e. to reduce the maximum demand in those cases where the machineries are expansive, and it is worth to reduce their capacity installed.

The cool storage operation strategies are often divided in full and partial storage. While partial storage is used for the demand limiting mentioned before and it consist in meeting just a portion of the on-peak cooling load from storage, a full storage system transfers the entire on-peak cooling load to off-peak periods to take advantages of the two-price difference and save on the electricity bill (Fig.5.12).

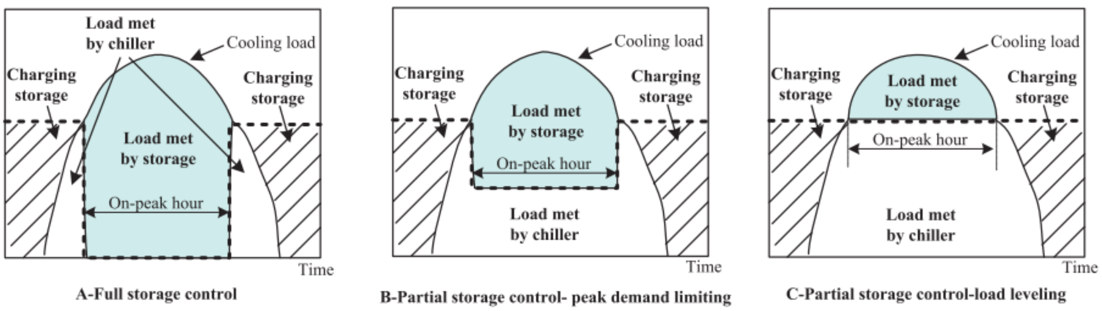


Figure 5.12 - TES strategies [30]

So, in a full storage, or load shifting, system the refrigeration equipment operates at full capacity during the off-peak hours of the day, storing the excess energy. Instead it is turned off during

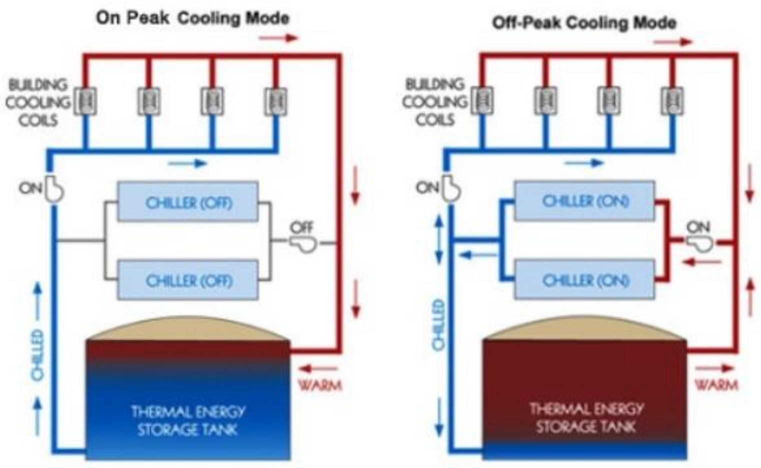


Figure 5.13 - TES control [30]

the on-peak hours discharging the cool storage to meet the load as in Fig.5.13. Such a system requires relatively large refrigeration and storage capacity and it is attractive when there is a relevant difference between the two period prices [15].

This is the case of the factory in object, in fact it is remembered that the total refrigeration capacity installed is of 975 kW_{th} when the maximum load registered is of 650 kW_{th}. This mean that the chillers could be used at maximum capacity to store the excess in the off-peak hours. Moreover, it is also remembered (paragraph 4.2.1.) in the following Tab.5.7 the high price difference between the P6 hours (that could be viewed ad off-peak hours) and P1-5 hours (that are the day time hours so the on-peak ones) that e.g. when comparing the P1 with the P6 charge rate is almost the 50%:

	P1	P2	P3	P4	P5	P6
TE cost [€/kWh_{el}]	0,09515	0,08348	0,07177	0,06405	0,05804	0,04684

Table 5.7 - Electricity cost for each of the six periods

So, the system configuration selected is the one schematized in Fig.5.14 below. In this way the chillers can fill the storage, supply the load or the both things, thanks to the regulation valves. In the while time the water returning from the load goes in the chiller to be cooled again, in the storage if it is being discharged to keep the water volume constant or the both things.

Moreover, due to the working temperature difference of the load, that is remembered to be between 14 and 19°C, it is needed to leave the actual heat exchanger to allow the supply of refrigeration at the low temperatures of the chillers (7 and 12°C). A solution that would seems possible is to rise the working temperatures of the chillers, but it is not possible for the electrical chillers due to pressure problems (note that they already exchange the refrigeration energy trough the 700 kWh_{th} heat exchanger).

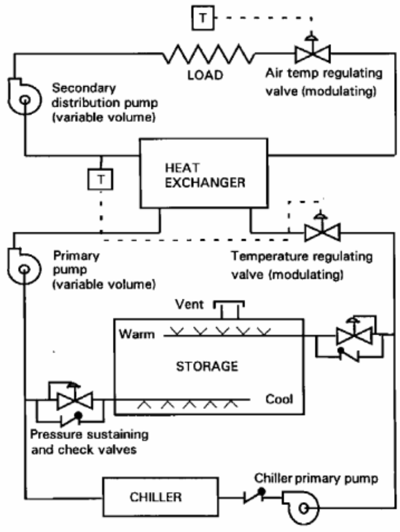


Figure 5.14 - New water cooling system scheme. The chiller represents the parallel of the 3 electrical chillers (already in parallel) with the absorption chiller.

There are several ways of storing the thermal energy but being already present a big cylindrical tank of 800 m^3 filled with water to extinguish fires, the choice has been to go for the sensible TES. The possibility of using it comes by the fact that there is no difference in extinguish a fire with ambient temperature or chilled water if the water volume inside is kept constant, and this is always true for the stratified storage tank. In the next section this technology will be explicated to understand its working principles.

5.3.2. Sensible heat storage physical principles

This kind of energy storage relies solely on the sensible (no phase change or latent energy) heat capacity of water and the temperature difference between the chilled water stored in the tank and the warm return water from the load. Maximizing this temperature delta maximizes the sensible energy storage capacity per unit of water and so minimize the size of the storage tank. To remember that in this study there is no need of building the tank, so the volume is already given as a constrain to be respected. The advantage of this technology is that there is no need for secondary coolants or heat exchangers.

For this project, due to the electrical & absorption chillers working conditions (see relative chapter), the maximum temperature difference is of 5°C. Moreover, it is remembered that the volume available is 800 m^{3,} so the energy stored is:

$$Emax = V\ Cp\ \Delta T\ FOM =$$

$$= 800\text{m3} \cdot 4{,}186\ \frac{KJ}{Kg \cdot K} \cdot 1000\ \frac{Kg}{m3} \cdot 5{,}00\ K \cdot 0{,}90 \cdot \frac{1}{3600}\ \frac{kWh}{kJ} \backsimeq 4190\ kWh$$

Where the parameter FOM is a kind of efficiency of the storage. In particular it is the ratio between the refrigeration energy removed from the storage and the refrigeration energy theoretically available. It takes into account the various losses that will be better explained further on in this section. Its value will be estimated from the simulations, but it can be assumed as 90%.

Chilled water storage is based on maintaining a thermal separation between cool charged water and warm return water. This separation can be achieved in several ways:

- Stratification
- Multiple tank
- Membrane or diaphragm
- Labyrinth and baffle

The stratified chilled water TES is generally acknowledged as the simplest, most efficient and most cost-effective method. This makes the choice of this study, that it is remembered to be obligated due to the fire service water tank restriction, well-motivated.

5.3.3. Thermal stratification

Stratified chilled water storage tanks rely on the natural tendency of water to form horizontal layers at different temperatures due to its density, that is directly proportional to its temperature. In fact, as water get colder it becomes denser, so the cool water from the chiller that goes inside the tank has the tendency of collecting and stabilizing in the lowest regions, while the warm water from the load will collect in the upper regions. The water density has this behavior till it reaches the 4°C, then below this point it becomes less dense until it freezes at 0°C (at atmospheric pressure), but for the temperature ranges of the chiller in study, that are between 7 and 12°C, this fact is not relevant.

Well-designed stratified chilled water storage tanks can deliver 85 to 95% of the stored energy as useful cooling, the rest is unavoidably dissipated. This is considered by the FOM parameter. They achieve the necessary separation between lower cold zone water and warm upper zone water by creating and maintaining the so-called thermocline that in the best case, is a stable and sharply defined temperature transition layer (Fig.5.15). The thermocline prevents cold water below from mixing with the warm water above, fact that would implies high losses.

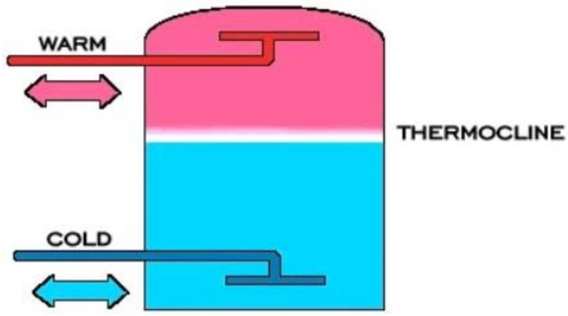


Figure 5.15 - Division of the cold water layer at the bottom from the lighter hot (warm) water layer that stays on the top. In the charging mode the blue arrow is directed on the right and the red on the left so the thermocline goes up. In the discharging mode instead, the opposite happens.

During the charging cycle, cool water from the chilling equipment enters the tank through the appropriate designed diffusers at the bottom, and warm water exits the tank at the top. As the volume of cold water increases a correspondent part of warm water volume is removed, keeping the volume constant and moving the thermocline upward. During the discharging cycle the flow of water is reversed. The diffusers responsible of keeping this functioning should be properly designed to permit the water to gently flow into and out the tank, minimizing turbulence and leaving the thermocline undisturbed.

Expansion or degradation of the thermocline can be due to:

- Heat transfer from the ambient
- Thermal diffusion in the storage tank
- Axial wall conduction
- Mixing during charging and discharging

As thermocline degrades, the volume of usable chilled water is reduced lowering the percentage of stored energy as useful cooling. For example, leaving the charged tank idle could lead to the complete degradation to such an extent that all the water reaches an unusable temperature. This happen with long period of inactivity depending on the size of the tank, the insulation value and other factors.

In a well-designed tank, thermocline thickness ranges from about 0.3 to 1 m, depending on diffuser design and the age of thermocline. The Fig.5.16 illustrates an example of a typical temperature profile along the height of the tank. In this case approximately 1m of unusable thermocline separates cold water at 4°C and warm water at 14°C.

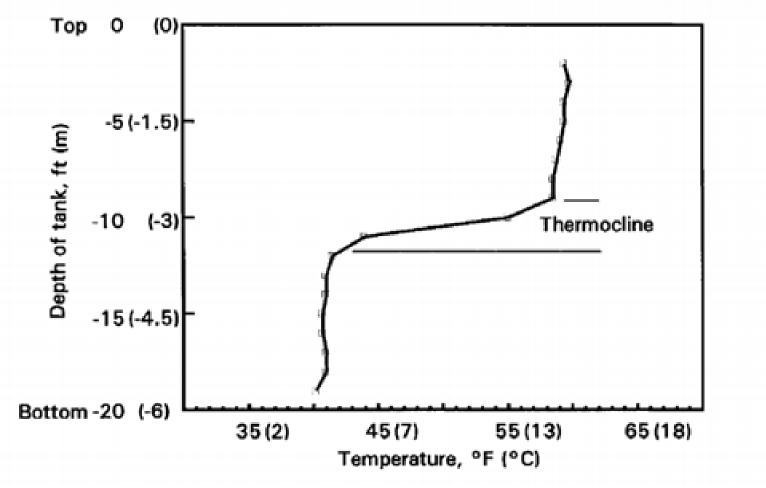


Figure 5.16 - Typical stratification temperature profile

5.3.4. Tank shape

The tank design includes foundation, tank construction, coatings, insulation, piping and diffusers. For this study the already built water deposit for firefights use next to the factory will be retrofitted as TES, so there is no need of construction lowering the initial investment cost.

The tank present is a flat-bottomed vertical cylinder. This shape is the most used one for stratified tank thanks to the low surface-to-volume ratio that implies low thermal losses to the ambient. It has an internal volume of 800 m^3, is made in cast-in-place concrete and it has foundations below the ground despite showing the most of its body above the surface.

The aspect ratio (A_r), i.e. the height to diameter ratio of the project tank is near to the unity. In fact, the diameter measures 10 m and the height is slightly higher i.e. of 10,19 m.

5.3.5. Diffusers design

In a stratified chilled water TES, separation of warm and cold water is accomplished only by careful diffusers design. They are needed to introduce water gently into the tank in a gravity current, to permit the formation and maintenance of the thermocline, that is the physical phenomenon responsible of the separation needed.

There are two diffusers in a stratified tank, one situated in the bottom and the other in the top. They can be of different shapes:

- Radial disk
- Multiple radial disk
- Octagonal
- ‘H’ shaped
- Square

While the H-shaped and the square ones are best suited for rectangular tanks, the octagonal and radial shapes are the most employed for the cylindrical tanks like the one studied. Various authors like Fiorino [10] or Wilndin and Truman [11] successfully control the octagonal headers. It could be either in single, double or multiple configurations. Due to cylindrical shape of the present deposit, for this project, a double-octagon diffuser system is chosen.

Double-octagonal diffusers are constituted by two concentric octagonal shaped pipes as showed in Fig.5.17 on the right. A series of equally sized, shaped, and spaced lateral slot openings are cut into the top of the straight section of the upper diffuser (hot water) and into the bottom for the lower diffuser (cold water). This symmetric design ensures an equal subdivision of the flow exiting in both radial inward and outward directions.

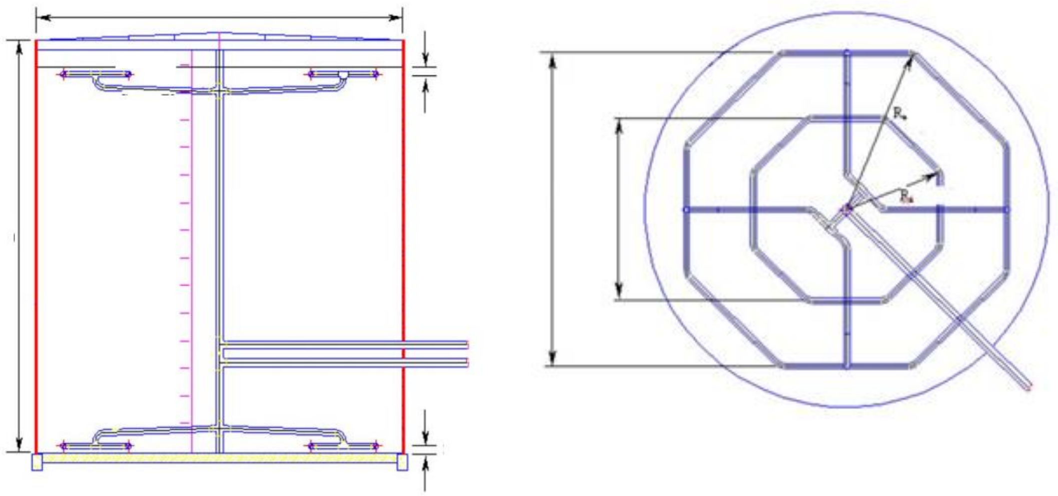


Figure 5.17 - Double ring octagonal diffuser scheme. On the left, vertical cross section. On the right, circle cross section of the tank at the top/bottom

To ensure the proper water flow that avoid the warm and cold water mixing, these diffusers must be designed with the appropriate Froude Number and taking care of the openings design. Instead, to minimize the thermocline degradation the dimensionless number to control is the Reynolds one.

The Froude number is the dimensionless ratio of the inertia force to the buoyancy force acting on a fluid.

$$Fri = \frac{q}{(g\ hi^3\ \frac{\Delta\rho}{\rho_o})} \qquad where \quad \Delta\rho = \rho_i - \rho_o \quad , \quad q = Q/L_d$$

Where q is the flow per unit length of the diffuser, hi is the minimum inlet opening height (see Fig.5.18 or the lower diffuser it is the distance between the bottom of the pipe and the tank floor), ρi is the density of inlet water, ρa the density of ambient water, Q maximum flow rate and

L_d the effective diffuser length (for the case of discharge by diffuser in two direction 180°C apart, it is twice the actual physical length of the diffuser).

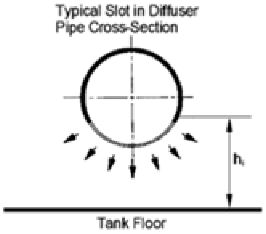


Figure 5.18 - Distance of the diffuser pipe from the top/bottom

Defined in this way the Froude number should be around 1 to accept the geometry of the diffusers. In this way the buoyancy force in the inlet flow is greater than the inertial force, and a gravity current, that creates the stratification, is formed. This condition is used to define the required inlet height hi, defined as the vertical distance occupied by the entering flow.

The Reynolds number instead, is another dimensionless parameter that asses if there is a possible mixing above and below the thermocline with its consequent degradation. It is the ratio of inertial to viscous forces.

$$Rei = \frac{q}{\nu}$$

Where q is the same of before and ν is the kinematic viscosity of inlet water.

The lower is the Reynolds number the lower will be the mixing. It is controlled by adjusting the effective diffuser length L_d mentioned before. The acceptable values depend on the tank shape, but in general an upper limit of 850 is recommended. Wildin [12] compared three diffusers (two radial, one octagonal) operating at fixed Fri for different Rei and demonstrated that stratification increase as Rei decrease. His guidelines are to keep Rei close to 200 for ‘shallow’ tanks and to 2000 for deep tanks.

So, to respect all of these constrain it is decided to design the diffusers with a total length (two diffusers) L_d of 45m and an h_i of 0.044m. To note that the maximum flow rate comes from the simulations done in the excel spreadsheet. This ensure a Reynolds number of 690 and a Froude number of 1. The two radiuses are respectively 4.3m and 3.1m so to have the total length calculated (Fig.5.17):

$$P_o + P_i = 2 \cdot 8 \cdot \sin\frac{\pi}{8}(R_o + R_i) = 45\ m$$

Said that, the openings of the diffusers should be dimensioned and spaced to permit a uniform flow rate per unit length. Moreover, a uniform discharge velocity along the length of the diffusers is necessary to establishing the gravity current. Instead a non-uniform flow could create vortices. To maintain this uniform discharge velocity the pressure in the interior of the diffuser piping must be as close as possible uniform. Hudson [13] asses that this uniformity can be approximated by making the total opening area in any diffuser branch no greater than half the cross-sectional area of the branch pipe.

The distribution piping that connect the diffusers to the load and the chiller should be designed to be symmetrical relative to the vertical axis of the tank and to the horizontal central plane. This ensures an equal pressure at any two corresponding points in the diffuser piping under all load conditions. It also ensures a self-balancing avoiding entering in the dull tank to adjust the diffusers for uniform flow [10]. Moreover, the distribution piping should be designed to contain the flow velocity below the 0,3 m/s before the water reaches the openings. This helps to maintain the uniformity of static pressure inside the piping.

The two diffusers openings should be oriented to direct the fluid entering the tank toward the correspondent adjacent surface. In this way the fluid exiting the openings encounters a boundary and is forced to spread horizontally to merge with the adjacent fluid exiting the other openings. In other words, thanks to this strategy the fluid doesn’t gain upward or downward momentum in correspondence respectively of lower and upper diffuser, avoiding the unwanted mixing.

To minimize mixing at the openings the maximum flow velocity before the water reaches the opening should be between 0,3 and 0,6 m/s, and the center-to-center distance between the openings should be kept less than about twice the opening height in the design phase.

5.3.6. Combination of the technologies and storage control strategy

To consider all the data an excel spreadsheet is employed. It consists in a table with the rows corresponding to the hours and various parameter in the columns. It takes input values and check the energy balance of the general configuration.

The inputs values are:

- **Refrigeration load**: it comes from the measurements (paragraph 4.4.2)
- **Solar system electricity supply**: it comes from the PSOL simulations, it is the hourly energy generated by the photovoltaic panels
- **Compressor load**: it corresponds with the compressor electricity consumption and it comes from the relative measurements (paragraph 4.4.3)
- **Compressor heat recovery percentage**: it is the percentage of the total compressor electricity consumption that can be recuperated between the absorption chiller

operating temperature. It is the 28% of the compressor load as studied in the paragraph 4.3.2

- **Storage maximum energy content**: is equal to
$$Emax = V\ Cp\ \Delta T\ FOM$$
- **Figure of merit (FOM)**: it corresponds with the percentage of the storage energy that can be utilized. At first it is assumed to be 90%. It will be modified after the studying of the mathematical model in the next paragraph. It multiplicate the energy produced by the chillers to be stored to compensate the loss and the discharge energy as it is defined.
- **Absorption chiller nominal refrigeration power**: it is needed to dictate the maximum refrigeration output of the Absorption chiller, so to size it
- **Absorption chiller inlet water temperature**: it is fixed at 95°C as it comes from the oil-water heat exchanger of the compressor
- **Absorption chiller COP:** Being the generator temperature fixed it is function only of the cooling water inlet temperature, calculated from the ambient temperature as explained in the paragraph 5.2.2
- **Electrical chiller COP:** It is calculated from the ambient temperature as explained in paragraph 4.3.4.
- **Ambient temperature:** It is the hourly external temperature and it comes from the PSOL software
- **Chiller temperature range**: due to the configuration of the system, that put the absorption chiller in parallel with the electrical chiller, it is the same for all the chillers i.e. fixed to be between 7 and 12°C
- **Electricity price**: It comes from the paragraph 4.2.1, it is the hourly electricity price

The principal parameters are:

- **Compressor heat recovery**: it is calculated multiplying the compressor load by the heat recovery percentage
- **Absorption chiller refrigeration supply**: is equal to
$$\text{Compressor heat recovery} \cdot \text{COP}$$
And it can return at maximum the value of the nominal power chosen as input
- **Electrical chiller refrigeration supply**: It is divided in the refrigeration produced consuming the electricity generated by the photovoltaic panels (always during the day time, when there is the sun) and in the refrigeration produced consuming the electricity purchased from the grid (always during the night time, when the electricity cost is at minimum, i.e. at the P6 band)
- **Storage filling**: it is true from 00:00 to 07:00 i.e. when the electricity price is the lowest (P6 band, 0.04684 €/kWh_{el}) and if the storage is not full of chilled water at 7°C.

- **Storage energy content**: it is the parameter that can vary from 0kWh$_{th}$ (empty storage, i.e. full of water at 12°C) to the maximum content calculated before of 4186kWh$_{th}$ (full storage, i.e. full of water at 7°C).
- **Chilled water flow rate charging the storage:** is calculated as:

$$m_{f,ch} = \frac{energy\ to\ storage}{c_f \Delta T}$$

- **Chilled water flow rate discharging the storage:** is calculated as the charging one but with the energy going from the storage to the heat exchanger

All of them are instantaneous power (kW$_{th}$) and being the time discretized in hours they are the hour average power, but they can be seen also as energies consumed in the hour (kWh$_{th}$).

Due to the low prices of electricity in the night-time (P6) it is decided to adopt a full storage control strategy. But there is a difference with the normal application in the air conditioning field, in fact, in this case the refrigeration load in the night hours is not null (check load curves Ann.8) so it is firstly needed to saturate it, and store only the surplus of energy. This is easier to understand looking at the following Fig.5.8:

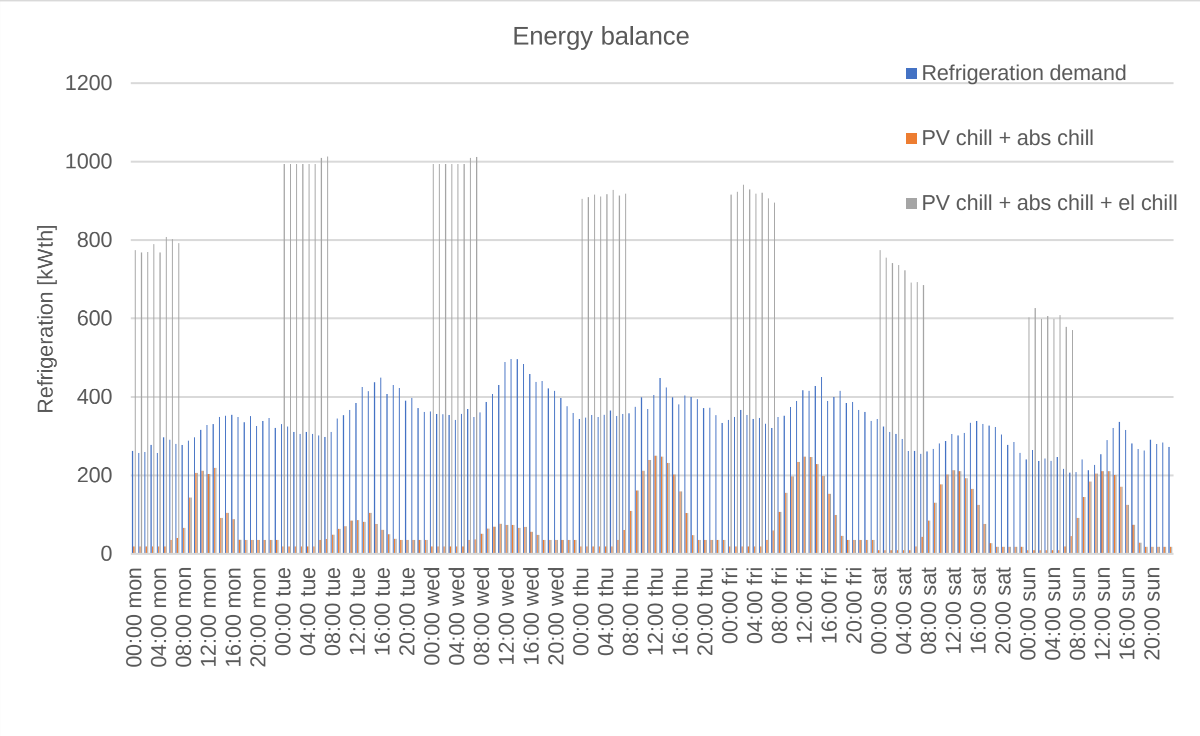


Figure 5.19 - Random week energy balance. The term “PV chill” indicate the refrigeration energy produced with the electricity coming from the photovoltaic field

The grey term is the sum of all the refrigeration produced, and only the subtraction between it and the demand will be stored, the rest is to consume instantaneously. Therefore, the electric chillers will be controlled to produce an amount of refrigeration enough to supply the following day looking at the weather forecast (the load is easily predictable with the production, but the PV generation depends on the sun radiation).

With this strategy the results show a feasible saturation of the load for all the days, with a very rare possibility of reaching the maximum storage content. For those cases of wrong prediction, faults or storage problems the electrical chillers will be turned on also in the day-time thanks to their flexibility.

Another relevant aspect is the manutention of the electrical chiller, aspect that will be still possible due to the low production during the day-time (no need of back-up chiller assuming a possible functioning during the night hours and the maintenance during the day ones).

5.3.7. Mathematical model

To model the thermal storage the model studied by Nelson and Murthy [20] is used with the appropriate modification for the case in study. Is a one-dimensional transient heat conduction problem with two dependent variables. One is the temperature of the chilled water inside the tank (T) and the other is the wall temperature considered constant (T_w). For this work the interest is in the first one because, if the model works, it will show the formation and/or degradation of the thermocline therefore it will be useful to assess if the assumption on the FOM is correct. In fact, as said before the thermocline degrades due to heat transfer with the ambient, thermal diffusion in the storage tank, axial wall conduction and mixing during charging and discharging.

As can be seen in Fig.5.19 the tank is divided into N equal slice of the cylinder that represent it, and it is assumed that each slide has a uniform heat temperature (1-dimensional). The following governing equations hold:

$$\frac{\partial T}{\partial t} = \alpha_f \frac{\partial^2 T}{\partial x^2} \pm \frac{\dot{m}}{\rho_f \, A_f} \frac{\partial T}{\partial x} + \frac{h_i P}{A_f \, \rho_f \, c_f}(T_w - T) \quad (\pm respectively\, for\, charging/discharging)$$

$$\frac{\partial T_w}{\partial t} = \alpha_w \frac{\partial^2 T}{\partial x^2} + \frac{UP}{A_w \, \rho_w \, c_w}(T_\infty - T) - \frac{h_i \, P}{A_w \, \rho_w \, c_w}(T_w - T) \quad where\ U = (\frac{1}{h_o} + \frac{\delta_{ins}}{k_{ins}})^{-1}$$

The initial conditions respectively of the water and wall temperature are inserted as a function:

$$T(x, 0) = f(x)$$

$$T_w(x, 0) = f_w(x)$$

They can be a simple constant value (7°C for “full” storage, 12°C for “empty” storage), the temperature distribution founded in the previous simulation for continuity or a function that shapes the ideal thermocline distribution as derived by Waluyo and Amin [21], that has the form(see Fig. Ann.14):

$$f(x) = T(x, 0) = T_c + \frac{T_h - T_c}{1 + 10^{(C-X)/S}} \quad where\ C, S\ are\ constant\ for\ giving\ the\ shape \quad Eq.(4)$$

The boundary conditions for the charge cycle are:

$$\frac{\partial T_t}{\partial x} + \frac{h_t}{k_f}(T_\infty - T_\mathrm{t}) + \frac{\dot{m}c_f}{k_f\,A_f\,Z_{ch}}(T_1 - T_t) \quad charge\ cycle\ \ x = 0$$

$$\frac{\partial T_b}{\partial x} - \frac{h_b}{k_f}(T_\infty - T_\mathrm{b}) - \frac{\dot{m}\,c_f}{k_f\,A_f\,Z_{ch}}(T_u - T_b) \quad charge\ cycle\ \ x = L$$

For the discharge cycle:

$$\frac{\partial T_t}{\partial x} + \frac{h_t}{k_f}(T_\infty - T_\mathrm{t}) + \frac{\dot{m}\,c_f}{k_f\,A_f\,Z_{disch}}(T_d - T_t) \quad discharge\ cycle\ \ x = 0$$

$$\frac{\partial T_b}{\partial x} - \frac{h_b}{k_f}(T_\infty - T_\mathrm{b}) - \frac{\dot{m}\,c_f}{k_f\,A_f\,Z_{disch}}(T_N - T_b) \quad discharge\ cycle\ \ x = L$$

(Please note that for the static mode the 3rd term is null because the mass flow rate is null)

Where the Z parameter is the mixing coefficient that consider the effects of mixing near the top and the bottom during the charging or discharging developed by the same authors of the model in another study [22]:

$$Z_{ch/disch} = 1.688 \times 10^4 (\frac{R_{e,ch/disch}}{R_{i,ch/disch}})^{0.67}$$

The nondimensional number employed are the Reynolds and Richardson ones that can be written as follow (attention that Reynolds is not the same used in the paragraph 5.3.5 for the diffusers):

$$R_{e,ch/disch} = \frac{w_{f,ch/disch} D}{\nu_f}$$

$$R_{i,ch/disch} = \frac{gD}{w^2_{f,ch/disch}}$$

Where w_f is the velocity of the fluid assumed to be the one obtained when a mass flow rate pass in a cylinder section. This correspond to the ideal case of diffusers that spread the water flow rate uniformly in the tank:

$$w_{f,ch/disch} = \frac{m_{f,ch/disch}}{\rho_f A_f}$$

Instead for the wall temperature boundary conditions it is assumed that it not varies in the extreme points:

$$\frac{\partial T_w}{\partial x} = 0 \ at \ x = 0 \ and \ x = L$$

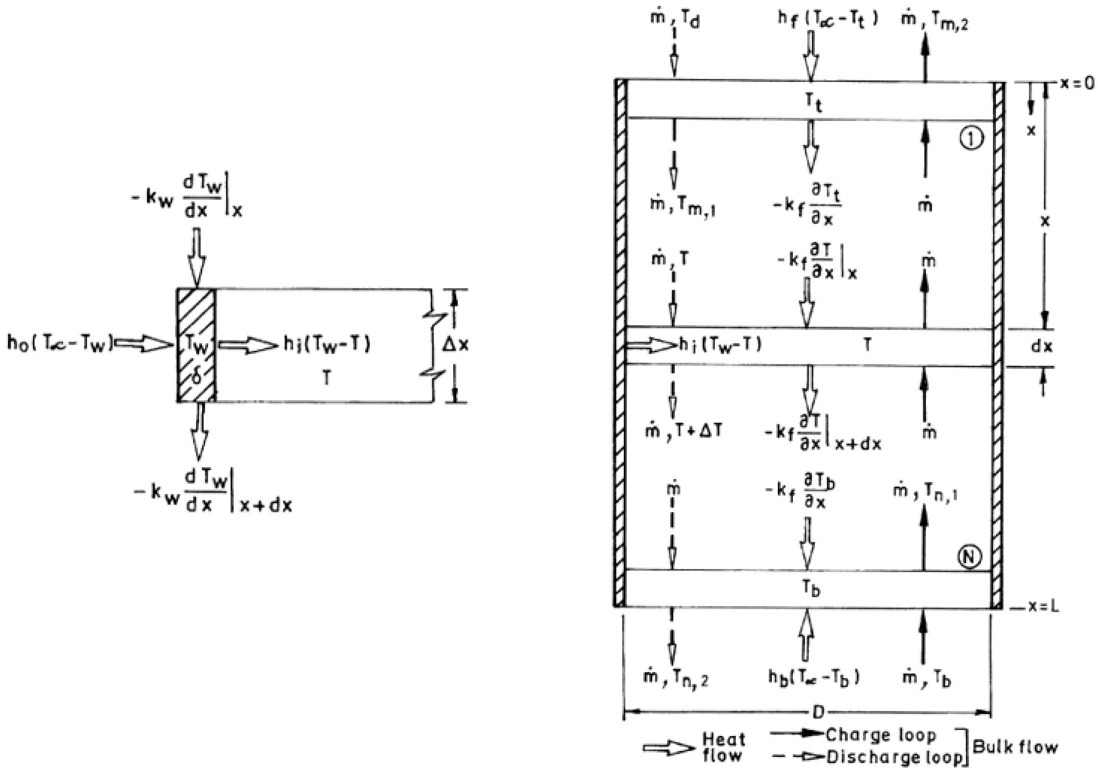


Figure 5.20 - Thermal storage tank infinitesimal element model scheme. The insulation is not represented in the wall of the left figure, but it is considered as thermal resistance.

To see the solution of this problem a numerical method is needed due to the impossibility of finding an analytical solution. The authors of it use the Crank Nicolson method nondimensionalizing the system, but in this study, it is solved with a matlab function for general partial differential equation systems. The code is reported in the Ann.15. It consist in a function that extimate the solution recalling other three functions, one for the governing equations, one for the initial conditions and one for the boundary conditions. Apart from this part, the code is impostated to view graphically the solution for each hour as it is simulated in the excel spreadsheet, despite it simulate the solution with a time step discretization of 1 s. The abscissa that rapresent the space variable x that goes from 0 to L is discretized in 40 equal spaced nodes (N=40). A problem that arised is that the solution shown a noisy behaviour, so to view it is smooted with an apposite function of matlab.

Moreover, the code is modified to give in input a water mass flow rate of charging or discharging variable for each hour as calculated in the hourly simulation of the year. The same is done for the hourly ambient temperature, an important parameter for calculating the heat infiltration or loss to the outside of the tank. This is not done instead, for the convective heat transfer coefficient of the water and the air that are assumed the same for all the year. All the other parameters like the geometry, the thermophysical proprieties and the water inlet and outlet temperature (7 and 12°C) are given once as input and remain constant for all the simulations.

5.3.8. Simulations

Before performing the charging and discharging cases, the static mode is simulated to understand how the insulation affect the thermocline degradation. In all the other cases, due to the control strategy chosen, the storage is almost always active, performing periodical cycles between the night-time (charging, low electricity price) and the day time (discharging, high electricity price). It remains inactive only if the storage is full or if it is empty and there isn't a surplus of energy to charge it when is empty, but this happen just for few hours.

So, two simulations are done for two days of 8 hours of inactivity of the storage, one for the winter one for the summer. The results, depicted in Fig.5.20 below, shown how fast the thermocline degrades without a layer of insulator on the tank due to the convective heat exchange with the external environment. For example, in the summer case, after 8 hours the temperature difference, that is initially given as 5 K with the temperature distribution of Eq.4, reduce to only 3 K. Another aspect that arises is how the temperature of the water in the top and bottom tends to the external one due to the absence of an inlet/outlet flux at the desired temperature as it happens during the normal operation.

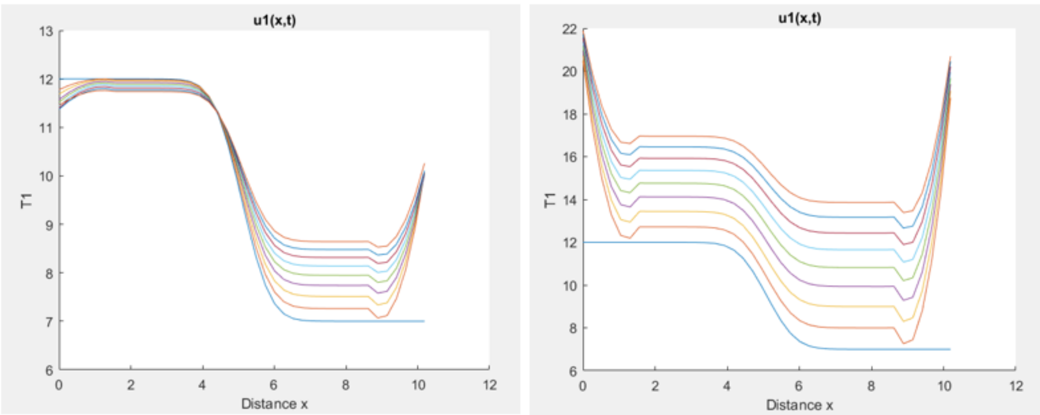


Figure 5.21 - Static mode simulations without insulation for 8 hours of inactivity. On the left winter case with an external temperature average of 10°C and on the right, summer case with an average of 25°C

So, it is decided to cover the water tank with a layer of polyurethane as Yan and Wang [23] suggest in their study where they retrofit a fire service tank as it is done in the present document. But instead of using 0,1 m as they do, it is decided to use just the half of this thickness thanks to the good results that the static simulations shown, reported in the following Fig.5.21:

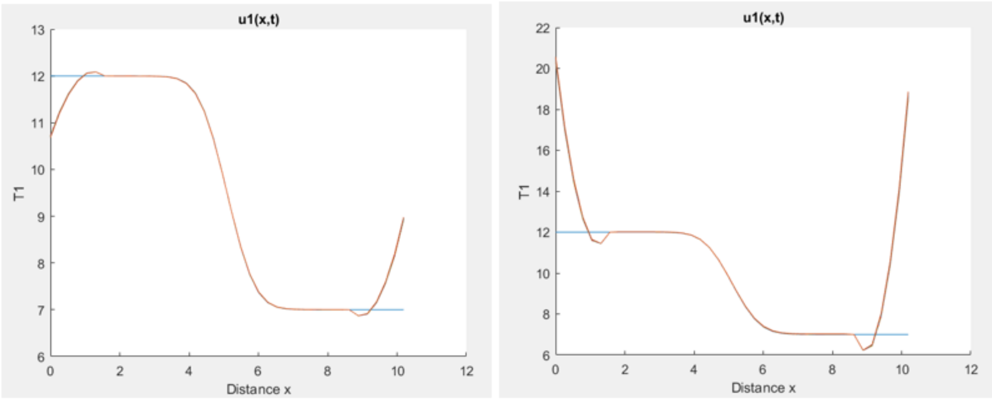


Figure 5.22 - Static mode simulations with 0,05m thickness of polyurethane insulation for 8 hours of inactivity. As before, winter case on the left and summer case on the right.

To assess the functionality of the storage during the daily operation cycles and to verify the FOM assumption the simulations are done for:

- 5th September

In this day a full operation cycle is performed, i.e. the storage starting for an initial “empty” state (all at the equilibrium return temperature from the load of 12°C) is filled till reaching the maximum capacity during the night hours, in fact, the hours of filling are 7 instead of 8 because the last hour the storage result “full”. The mass flow rate of charging is around 30 kg/s (one of the maximum registered) for all the 7 hours, with the assumption of a FOM equal to 90%. The results show the expected behaviour. In fact, for the last hour of the charging cycle (Fig.5.22 on the left) the storage reaches a uniform temperature of 7°C till x=2 m (near the top). The oscillating behaviour shouldn’t correspond with the reality, because it is due to the stability of the numerical model. After these 7 hours the storage is discharged for the next 15 hours during the day-time (Fig.5.22 on the right), reaching in the last hour a temperature distribution with the thermocline near the bottom and the outlet temperature still kept as 7°C as needed by the heat exchanger.

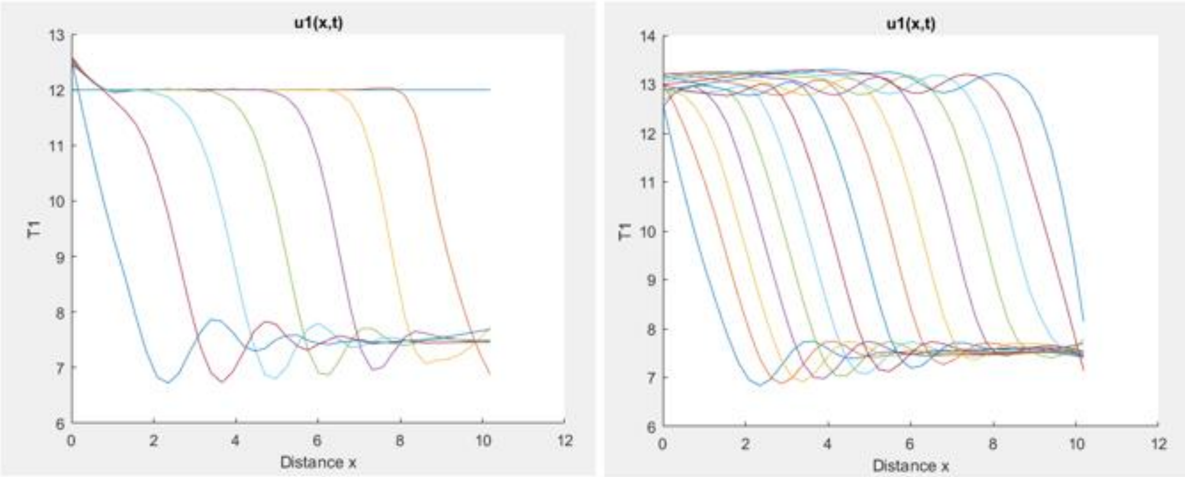


Figure 5.23 - Result from simulating the 5th of September. On the left is reported the charge cycle, and on the right the discharge one.

- 2nd December

In this day, due to the low demand, the to store and so the water flow rate is at the lowest values (average of 12,65 kg/s) so it is performed a partial cycle of charging-discharging. Also, in this situation the results are as expected with the extreme temperature maintained with a FOM of 90%.

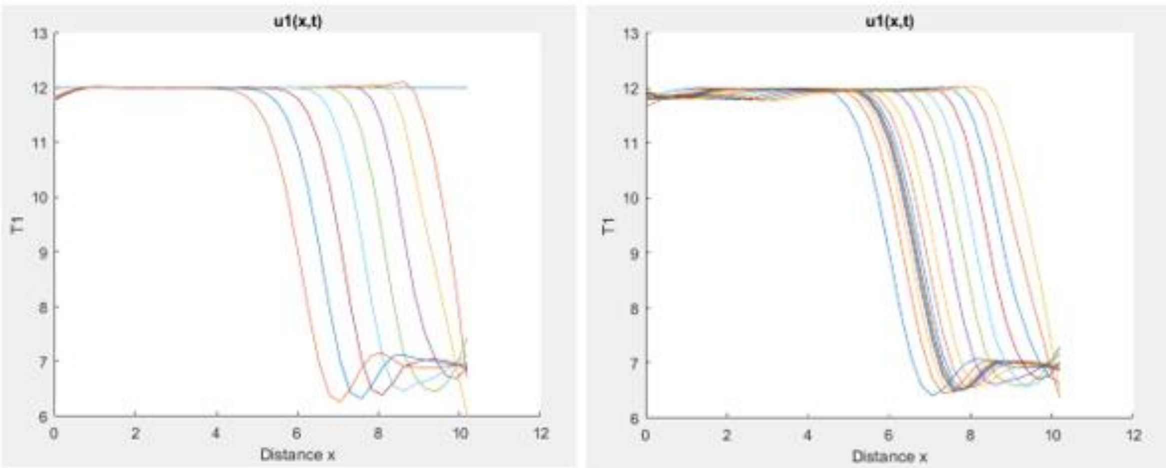


Figure 5.24 - Result from simulating the 2nd of December

- 29th October

On this day of the year, the average mass flow rate is measured (around 23 kg/s) and the results respect all the constrains.

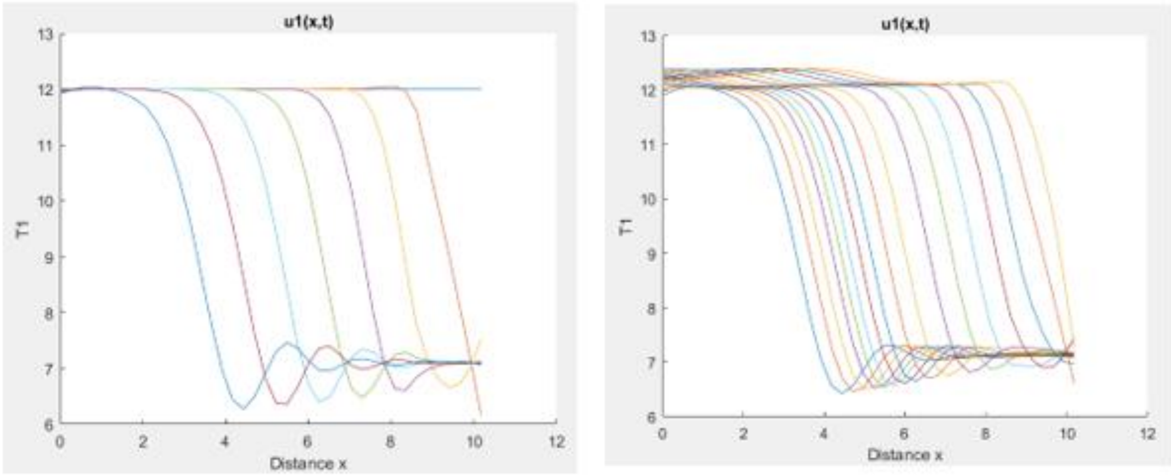


Figure 5.25 - Simulation on an average condition day

- 2nd June

This day is simulated to see how a high external temperature (average 18°C in the night and 25°C during the day) affect the storage. From the results of Fig.5.25 both on the top and on the bottom the temperature distribution departs from the nominal conditions of the chillers. This will imply different charge on the heat exchanger, and the mixing with the send and return of the chillers at different temperatures implying entropy losses. This aspect could be compensated with a vary on the electrical chiller capacity in the day time.

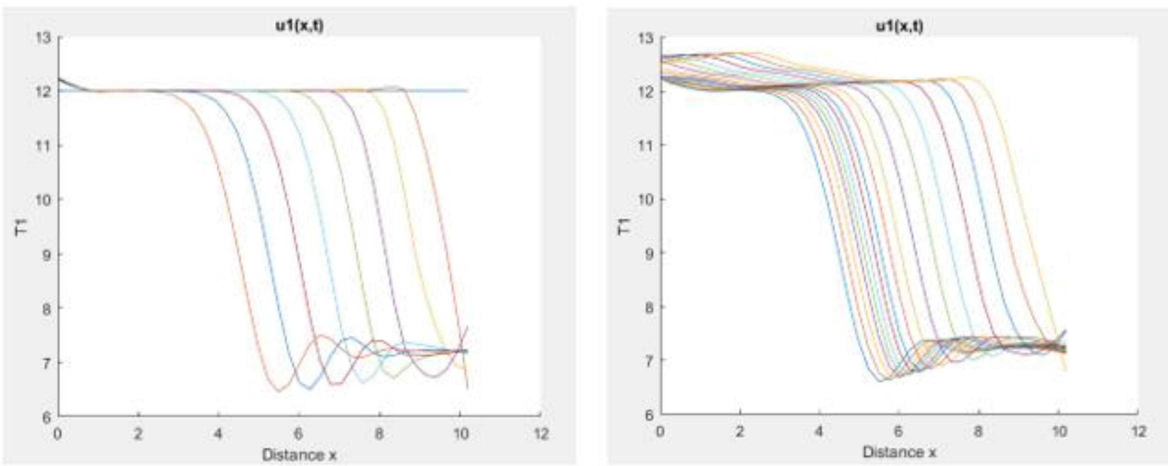


Figure 5.26 - Partial storage cycle in a hot day of June

Given those results the assumed value of 90% for the FOM is confirmed.

5.3.9. Cost of installation

For this third technology, differently from the previous other two, the cost doesn't come from a real provider offer. Instead, it was estimated from the study of Yan and Wang[23] in which more than a building fire service water tank is retrofitted as chilled water storage. They studied three different cases and one of them was the case of a low ΔT inside the tank, i.e. 5°C like for this study. Therefore, it is chosen and the costs per cubic meter and total are reported in the following tab.5.9:

	Cost [€/m3]	Expenditure [€]	%
Insulation	30,68	24.541,44	23%
Pumps	37,49	29.990,40	28%
Electric actuated valves	20,24	16.192,00	15%
Water distributors and pipelines	22	17.600,00	16%
Others (10%)	24,61	19.690,88	18%
TOT	135,02	108.014,72	

Table 5.8 - Costs of retrofitting a firefight water deposit in a stratified chilled water TES

The insulation cost is reduced of the 40% due to the use of half of the material that it is used in the reference. The voice "others" contains the various sensor like the pressure, flow rate and temperature needed to control the operation of the storage. The temperature sensors are mounted on a single column, as depicted in Fig.5.17 in the purple line, to monitor the real state of the thermocline.

The annual maintenance cost instead, is taken from another reference and it amounts to the 3% of the total investment one [23]. In particular, it considers the cost of the electrical energy needed to pump the water flow inside and outside the tank and the make-up water to integrate the possible water losses that would cause a loss of energy available and a danger for firefights security reasons. This make-up water will be introduced through the upper diffuser to not interfere with the thermocline

5.4. Economic & Environmental study

5.4.1. Energy balance

Once verified the predicted functioning of the storage, all the year is simulated with the excel spreadsheet keeping the value assumed of the FOM. The energy balance is the following:

	Refrigeration energy [kWh_{th}]	
Total refrigeration needed (load/demand)	2.751.663	-
Absorption chiller refrigeration generated	230.655	8,38%
Chiller alimented by PV refrigeration generated	368.894	13,41%
Chiller alimented by electricity refrigeration generated	2.253.930	81,91%
TOT refrigeration generated	2.853.478	103,70%
Electrical chiller refrigeration energy consumed instantaneously	916.788	-
Refrigeration energy to storage	1.337.636	-
Refrigeration energy from storage (energy stored)	1.150.119	-
Refrigeration energy lost due to FOM	187.517	14,02%
Load supplied	2.853.972	103,72%

Table 5.9 - Final energy balance that comes from the simulation of the three technologies

It reports the sum of the refrigeration energies generated for each hour of the year, that takes in input the demand, weather forecast and compressor load of the 2017. This sum exceeds the needs of a 3,7 % and this is due to the hourly step discretization of the storage that becomes full of a defect of ±1 hour. In fact, the energy lost due to FOM is the 4,02% higher than expected.

The voice “Electrical chiller refrigeration energy consumed instantaneously” is the term explained with the Fig.5.18 and must be considered when summing all the energies as follow:

$$Load\ supplyed = TOT\ refr\ gen = abs\ chill\ + PV\ chill + el\ chill$$

Where

$$el\ chill = el\ chill\ consumed\ instantaneously + energy\ lost\ due\ to\ FOM + energy\ stored$$

The Tab.5.10 instead, reports the saving that the installation of the three technologies would imply. It is useful for the economic analysis of the next section.

	Electrical energy [kWhel]
Electrical energy needed actual system	1.123.158
Absorption chiller electricity saving	94.147
Chiller alimented by PV electricity savings	151.289
Chiller alimented by electricity consumption	915.865

Table 5.10 - Electricity balance

All the month energy balances coming from the simulation are reported in the Ann.16.

5.4.2. Economic analysis

To evaluate the project from an economical point of view it is needed to understand if it is worth to invest or it is better to leave the water cooling system as it is. For this purpose, in this paragraph the two cases i.e. the “base case” and the “investment case” are compared. To do this, the Net Present Value is employed. It is calculated with the following formula:

$$NPV = \sum_{t=0}^{n} \frac{NCF(t)}{(1+k)^t}$$

Where NCF stay for Net Cash Flow, that is calculated for each year (t=1...n with n is the time horizon) as:

$$NCF(t) = Revenues(t) - Costs(t)$$

Where both the voices are calculated with a differential logic (investment case – base case) to consider only those revenues and costs generated from the investment project, as to say the entrance and losses that the company will have if decides to undertake the investment, but that won’t have in the opposite case (avoidable costs). For this it is important to define the base case. For example, in both the cases of buying or not an absorption chiller for recuperating the compressor waste heat, there will be a cost of pumping the chilled water to the injection machines, so this cost has not to be considered.

Another thing to pay attention with this method are the sunk costs, that are those voices of costs, like the maintenance of a substituted machine, that won’t be paid anymore in the case of investment. But for this case this is not relevant.

So, assumed a time horizon of 20 years that correspond both to the useful life of the photovoltaic system and the thermal storage the costs considered are:

- Initial investment costs: as reported at the end of each device section.
  Considered once at the year 0 for the two devices with a life of 20 years and two times for the absorption chiller that has to be changed after 10 years.

- Annual cost: considered the same estimated for each of the 20 years. It corresponds with the operating and maintenance cost of the technologies

The revenues considered instead, apart from the electricity saving of the absorption chiller and of the photovoltaic field, and from the thermal storage peak shifting (which savings are explained in the relative paragraph), are also the possibility of changing the power contracted as follow:

	P1	P2	P3	P4	P5	P6
Contracted power [kW]	2'200	2'200	2'200	2'200	2'200	2'800
TP cost [€/kW]	39.13943	19.58665	14.33418	14.33418	14.33418	6.54018

Table 5.11 - Possible change in the power contracted

This thanks to the peak shifting of the thermal storage too.

Therefore assuming also a degradation in the efficiency of the devices of 1% and an interest rate of 4% the results are reported in the following Tab.5.12:

	YEAR	0	1	2	3	4	5	6	7
ELECTRICITY COST	Average el cost ALL [€/kWhel]	0.0641 €	0.0648 €	0.0654 €	0.0661 €	0.0667 €	0.0674 €	0.0681 €	0.0688 €
	Average el cost PV [€/kWhel]	0.0703 €	0.0710 €	0.0717 €	0.0724 €	0.0731 €	0.0739 €	0.0746 €	0.0754 €
COSTS	Investiment	243'019.72 €	- €	- €	- €	- €	- €	- €	- €
	Annual (maintenance)	- €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €
TOT COSTS		243'019.72 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €
REVENUES	Power term saving	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €
	PV energy saving [kWhel]	151289	149776	148278	146795	145328	143874	142436	141011
	PV saving	10'632.75 €	10'631.69 €	10'630.63 €	10'629.56 €	10'628.50 €	10'627.44 €	10'626.37 €	10'625.31 €
	ABS CHILL energy saving [kWhel]	94147	93206	92274	91351	90438	89533	88638	87751
	ABS CHILL saving	6'038.49 €	6'037.89 €	6'037.29 €	6'036.68 €	6'036.08 €	6'035.48 €	6'034.87 €	6'034.27 €
	TES saving	11'274.95 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €
TOT REVENUES	TOT saving	56'502.73 €	56'613.81 €	56'612.14 €	56'610.48 €	56'608.81 €	56'607.14 €	56'605.48 €	56'603.81 €
	CF	-186'516.99 €	51'214.44 €	51'212.78 €	51'211.11 €	51'209.44 €	51'207.78 €	51'206.11 €	51'204.44 €
	CF actualized	-186'516.99 €	49'244.66 €	47'349.09 €	45'526.49 €	43'774.05 €	42'089.06 €	40'468.93 €	38'911.17 €
	CF actualized cumulated	-186'516.99 €	-137'272.33 €	-89'923.24 €	-44'396.76 €	- 622.71 €	41'466.35 €	81'935.28 €	120'846.45 €

	YEAR	8	9	10	11	12	13	14
ELECTRICITY COST	Average el cost ALL [€/kWhel]	0.0695 €	0.0701 €	0.0708 €	0.0716 €	0.0723 €	0.0730 €	0.0737 €
	Average el cost PV [€/kWhel]	0.0761 €	0.0769 €	0.0776 €	0.0784 €	0.0792 €	0.0800 €	0.0808 €
COSTS	Investiment	- €	- €	- €	12'005.00 €	- €	- €	- €
	Annual (maintenance)	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €
TOT COSTS		5'399.37 €	5'399.37 €	5'399.37 €	17'404.37 €	5'399.37 €	5'399.37 €	5'399.37 €
REVENUES	Power term saving	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €
	PV energy saving [kWhel]	139601	138205	136823	135455	134100	132759	131432
	PV saving	10'624.25 €	10'623.19 €	10'622.12 €	10'621.06 €	10'620.00 €	10'618.94 €	10'617.88 €
	ABS CHILL energy saving [kWhel]	86874	86005	85145	84294	83451	82616	81790
	ABS CHILL saving	6'033.67 €	6'033.06 €	6'032.46 €	6'031.86 €	6'031.25 €	6'030.65 €	6'030.05 €
	TES saving	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €
TOT REVENUES	TOT saving	56'602.15 €	56'600.48 €	56'598.81 €	56'597.15 €	56'595.48 €	56'593.82 €	56'592.15 €
	CF	51'202.78 €	51'201.11 €	51'199.45 €	39'192.78 €	51'196.12 €	51'194.45 €	51'192.79 €
	CF actualized	37'413.37 €	35'973.22 €	34'588.51 €	25'458.88 €	31'976.94 €	30'746.06 €	29'562.56 €
	CF actualized cumulated	158'259.82 €	194'233.04 €	228'821.55 €	254'280.44 €	286'257.38 €	317'003.44 €	346'566.00 €

	YEAR	15	16	17	18	19	20
ELECTRICITY COST	Average el cost ALL [€/kWhel]	0.0745 €	0.0752 €	0.0760 €	0.0767 €	0.0775 €	0.0783 €
	Average el cost PV [€/kWhel]	0.0816 €	0.0824 €	0.0832 €	0.0841 €	0.0849 €	0.0858 €
COSTS	Investiment	- €	- €	- €	- €	- €	- €
	Annual (maintenance)	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €
TOT COSTS		5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €	5'399.37 €
REVENUES	Power term saving	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €	28'556.53 €
	PV energy saving [kWhel]	130117	128816	127528	126253	124990	123740
	PV saving	10'616.81 €	10'615.75 €	10'614.69 €	10'613.63 €	10'612.57 €	10'611.51 €
	ABS CHILL energy saving [kWhel]	80972	80162	79361	78567	77782	77004
	ABS CHILL saving	6'029.44 €	6'028.84 €	6'028.24 €	6'027.63 €	6'027.03 €	6'026.43 €
	TES saving	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €	11'387.70 €
TOT REVENUES	TOT saving	56'590.49 €	56'588.82 €	56'587.16 €	56'585.50 €	56'583.83 €	56'582.17 €
	CF	51'191.12 €	51'189.46 €	51'187.79 €	51'186.13 €	51'184.46 €	51'182.80 €
	CF actualized	28'424.61 €	27'330.47 €	26'278.44 €	25'266.91 €	24'294.32 €	23'359.16 €
	CF actualized cumulated	374'990.61 €	402'321.08 €	428'599.52 €	453'866.43 €	478'160.75 €	501'519.91 €

Table 5.12 - Costs, revenues and cash flow yearly and accumulated of the years in exams

The NPV results positive of 501.519,91 € saying that an investment is probably rentable and so convenient to undertake.

The payback is calculated with the actualized Cash Flow form the payback function depicted in the Fig.5.26

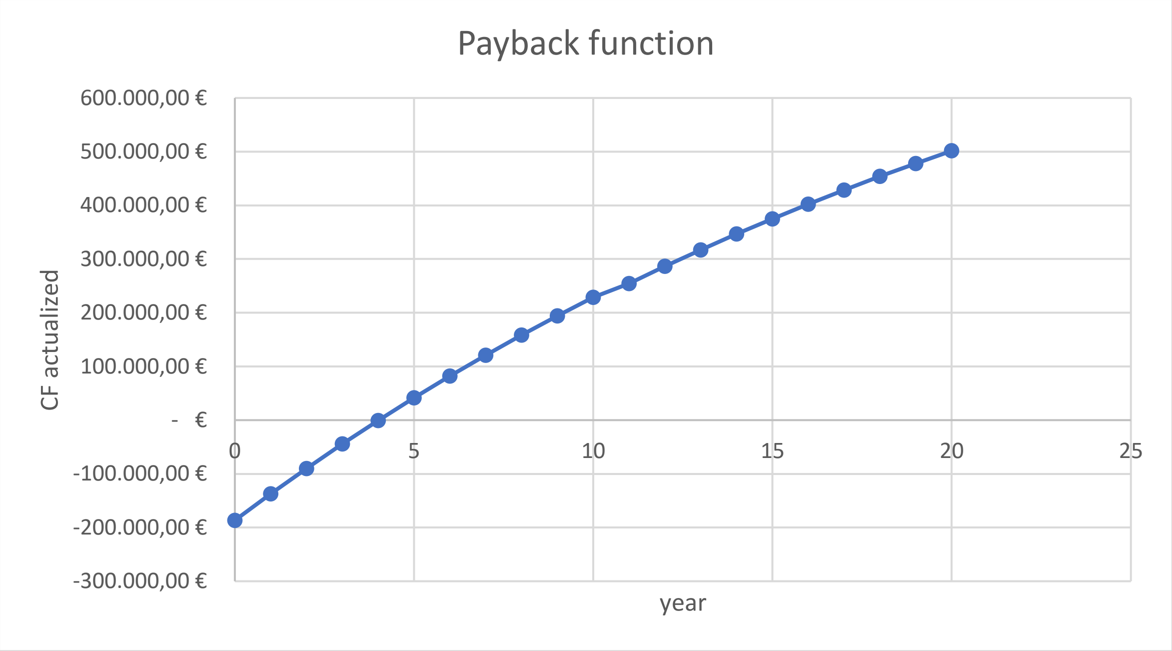


Figure 5.27 - Payback function

From the graph, it is seen that the investment starts to have a positive balance around the 4th year.

The profitability index, that is similar to the B/C (benefit/cost) of the WCM method is 1,97. It is a relative type indicator that measures the assicurated return from the investment project for each € of capital invested.

5.4.3. Environmental analysis

As introduced in the paragraph 4.5.1 to respect the target fixed for the year 2019 there must be a reduction of 138 MWh_{el} on the total electricity consumption. This correspond to an annual environmental saving of 47 tn_{CO2}.

If the three technology are installed the electricity saving will be of 207 MWh_{el} i.e. to avoid emitting in the air 70 tn_{co2} per year that correspond to 1.4120 tn_{CO2} for all the useful life of the machines. So, in the case of invest in the project the objectives will be widely reached.

Moreover, the thermal storage, that doesn't save directly electrical energy, contribute to shift the national peak in the night time, levelling the demand. This avoid the installation of new capacity for the Spain.

Step 6 & 7: Conclusions

The project objective was the cut of the electricity consumption to respect the emission limits imposed by the law and the internal policies. From the environmental analysis it is proven that investing in the three technologies studied is a realistic way to fulfil it. To enforce this result, the economic analysis shows a feasible rentability.

The three technologies, being applied on the same system that refrigerate the cooling water, have been sized after numerous simulations to reach a solution that permit their reciprocal utilization. While the renewable energy technology and the absorption chiller are necessary to the cut of greenhouse gases, the stratified thermal storage is the main source of economical saving and in a future where the solar thermal energy could become cheaper it could be used as thermal storage to contrast its intermittence.

The WCM approach has been a valid methodology to develop the project from the energetic analysis of the factory, focused on the model area, as to say the water cooling system to these conclusions in which is decided to conclude de pursuit with the steps 6 & 7. In fact, those last steps aim to standardize the project developed in one factory to all the other factory of the multinational company, procedure that could imply a better study of this project neutralizing those that could be seen as week points, like the study of a control system able to permit the operating conditions imposed, or the revision of the hydraulic system to asses which are all the instrument needed to permit its functioning.

Acknowledgments

I would like to thank the people of the company that spent their time giving me precious advices and the energies to bring this study to completion, in order of appearance: Jose Maria Belmonte, Guenda Hehmann & Daniele Rossin.

A special thank to the professor Oriol Gomis Bellmunt that accepted to be my formal director at the UPC of Barcelona and to Marcello Aprile from the part of the Politecnico di Milano university.

To my family and my friends, that have always been by my side. Thank you !

References

[1] Next. [Online]. Available: https://mynext.it/2016/06/cosa-vuol-dire-supportare-metodologie-wcm/.

[2] Harwell, Heat recovery from air compressors, GOOD PRACTICE GUIDE 238, 1993.

[3] "Rollair compressor," [Online]. Available: http://pdf.directindustry.it/pdf/worthington-creyssenssac/rollair-C-compresores-aire-40-125/7783-349693.html.

[4] "The workshop compressor," [Online]. Available: http://theworkshopcompressor.com/learn/compressor-types/rotary-screw-compressor/how-oil-injected-rotary-screw-air-compressors-work/.

[5] L. Mazzarella. [Online]. Available: http://tecnologia.assimpredilance.it/Costruire_Classe_A/06_Mazzarella_27ott10/ANCE_Mazzarella_2010_Parte_II.pdf.

[6] "The emission factors," [Online]. Available: https://www.eumayors.eu/IMG/pdf/technical_annex_en.pdf.

[7] IDAE, "Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red," 2011. [Online]. Available: http://www.idae.es/uploads/documentos/documentos_5654_FV_pliego_condiciones_tecnicas_instalaciones_conectadas_a_red_C20_Julio_2011_3498eaaf.pdf.

[8] "Valentin software," [Online]. Available: https://www.valentin-software.com/it/prodotti/tsol.

[9] M. Gentilini, Pompe di calore ad assorbimento, Università degli Studi di Bologna.

[10] "Johnson Controls," [Online]. Available: http://www.johnsoncontrols.com/.

[11] O. Ketfi and M. Merzouk, Performance of a Single Effect Solar Absorption Cooling System (Libr-H2O), Tipaza: Energy Procedia, 2015.

[12] R. Porumb and B. Porumb, Numerical investigation on solar absorption chiller with LiBr-H2O operating conditions and performances, Cluj-Napoca: Energy Procedia, 2017.

[13] "Engineering Toolbox," [Online]. Available: https://www.engineeringtoolbox.com/cooling-

tower-efficiency-d_699.html.

[14] R. STULL, Wet-Bu lb Temper ature from Relative Humidity and Air Temperature.

[15] timeanddate.com. [Online]. Available: https://www.timeanddate.com/weather/@3118240/climate.

[16] C. E. Dorgan, Design guide for cool thermal storage, Atlanta: ASHRAE, 1993.

[17] Fiorino, Case study ofa large,naturally slratified,chilled-waterthermal energy storage system, ASHRAE, 1991.

[18] T. Wildin, Performanceofstratified vertical cylindrical thermal storage tanks, Part I: scale model tank., ASHRAE, 1989.

[19] M. Wildin, Diffuser design for naturally stratified thermal storage,, ASHRAE, 1990.

[20] Hudson, Journal of the Environmental Engineering Division, ASCE, Vol. EE4, 1980.

[21] J. Nelson and S. Murthy, Parametric studies on thermally stratified chilled water storage systems, New York: Applied Thermal Engineering, 2005.

[22] J. Waluyo and A. Majid, "Temperature Profile and Thermocline Thickness Evaluation of a Stratified Thermal Energy Storage Tank," *International Journal of Mechanical & Mechatronics Engineering,* vol. 10, no. 01, 2010.

[23] J. Nelson and S. Murthy, "Experiments on stratified chilled water tanks," *Int. Journal of Refrigeration.*

[24] C. Yan and S. Wang, Retrofitting building fire service water tanks as chilled water storage for power demand limiting, SAGE, 2016.

[25] A. Hauer, Thermal Energy Storage, IRENA, 2013.

[26] P. G. I. System, "PVGIS," [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#.

[27] "Goldman Energy," [Online]. Available: http://goldman.com.au/energy/company-news/how-does-an-absorption-chiller-work/.

[28] M. J. Somarriba, CHILLED WATER TES TANK OVERVIEW.

[29] Y. Sun and S. Wang, Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: A review, Hong Kong: Elsevier, 2013.

[30] "Solargis," [Online]. Available: https://solargis.com/.

Complementary bibliography

- Directori de proveïdors, producTES i serveis d’eficiència energètica per a la indústria.
- “Estalvi i eficiència energètica en edificis públics.” Col·lecció quadern pràctic número 2.
- Presentació “Resum de la convocatòria de subvencions d’estalvi i eficiència energética 2010”. Com a exemple de cara a la propera campanya del 2011, encara per sortir.
- “Subvencions de l’Institut Català de l’Energia. Estalvi i eficiència energètica. Resum convocatoria 2010.”
- Fiorino, D.P. 1993. Energy conservation with thermally stratified chilled water storage. ASHRAE ***Journal*** 35(5):22